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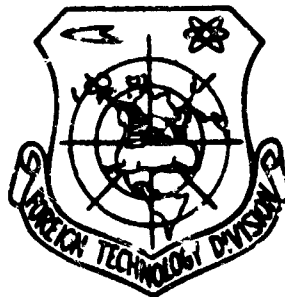
FOREIGN TECHNOLOGY DIVISION

AVIATION FUELS, LUBRICANTS AND SPECIAL LIQUIDS

by

A. F. Aksenov

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The book presents the methods of obtaining, the chemical composition of the operational properties, and the methods of controlling the applicable fuels, lubricants, and special liquids. Main attention is paid to the heat of combustion of fuels; to the stability of fuels, oils, of lubricants, and liquids under various operating conditions; to the pumpability of fuels and oils, the corrosion, antiwear, and antiseizing properties. Attention is also paid to fuels for supersonic aviation, promising lubricating materials, including solid lubricants, and promising liquids. The book is intended as a textbook for students of aviation higher educational institutions. It can be used by the technical-engineering staff of civil aviation, by audiences of the schools of civil aviation and by other specialists working in the area of the use of aviation fuels, lubricants, and special liquids. Orig. art. has: 120 figures, and 50 tables. [AM0139127]

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Jet Fuel						
Kerosene						
Synthetic Material						
Lubricating Oil						
Grease						
Solid Lubricant						
Rocket Propellant Production						
Aircraft Lubricant						
Supersonic Transport						
Pol Storage						
Fuel Supply Control						

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Л. Ф. АКСЕНОВ

АВИАЦИОННЫЕ ТОПЛИВА, СМАЗОЧНЫЕ МАТЕРИАЛЫ И СПЕЦИАЛЬНЫЕ ЖИДКОСТИ

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в качестве учебника
для вузов гражданской авиации

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

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Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
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К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.
The use of diacritical marks is preferred, but such marks
may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log

Aviation fuels, lubricants and special liquids. The 2nd publication, revised and supplemented. Aksenov, A. F. Publishing house "Transport," 1970, pages 1-256.

The book presents the methods of obtaining, the chemical composition of the operational properties, and the methods of controlling the applicable fuels, *lubricants,* and special liquids.

Main attention is paid to the heat of combustion of fuels; to the stability of fuels, oils, of lubricants, and liquids under various operating conditions; to the pumpability of fuels and oils, the corrosion, antiwear, and antiseizing properties. Attention is also paid to fuels for supersonic aviation, promising lubricating materials, including solid lubricants, and promising liquids.

The book is intended as a textbook for for students of aviation higher educational institutions. It can be used by the technical-engineering staff of civil aviation, by audiences of the schools of civil aviation and by other specialists working in the area of the use of aviation fuels, lubricants, and special liquids. Figures 120, Tables 50, bibliography 12.

INTRODUCTION

The development of aviation transport leads both to a further increase in the quality of the fuels, lubricants, and special liquids being used, and to an increase in their quantity.

Modern aircraft are complex machines which operate in various meteorological and climatic conditions. Fuel, oil, hydraulic systems and separate assemblies and aggregates should retain their efficiency at various loads and temperatures from -60 to several hundreds of degrees above zero, both at the atmospheric pressure on the earth, and at an altitude of 10-20 km. The tendency to obtain large powers with low engine weight and a carrying capacity with a small design weight of the aircraft leads to the maximum possible increase in the speeds of relative movement of contacting parts and contact pressures.

Modern aviation fuels, lubricants, and special liquids should satisfy a whole series of requirements, connected with economy, reliability, and longevity of work of aviation technology. Providing the most important requirement — the safe operation of aviation technology — in many respects depends upon the quality of the aviation fuels, lubricants, and special liquids. Therefore the fuels, lubricants, and special liquids used in aircraft should possess properties which provide for reliable and long-term work of the assemblies and aggregates under these complex conditions.

The properties of the fuels, lubricants, and special liquids, being used, even the very well selected for a given aircraft, change in the process of transportation, storage, and also directly in the aircraft even after servicing them.

The specialist who uses this or that type of aircraft must know not only the basic properties of fuel-lubricating materials, but also the changes in physiochemical properties under the influence of external factors. Without such knowledge it is not possible to create storage and transport conditions, or to select such operating conditions for the aircraft systems at which these changes will be minimum.

With the development of civil aviation the properties of the fuels, lubricants, and special liquids being used are naturally improved and their selection is enlarged, however, it is hardly possible to expect that this will completely satisfy the requirements of rapidly developing aviation technology. Therefore the problem of further improvement of the properties and of the expansion of the assortment of fuel-lubricating materials will always be actual. If today subsonic aircraft fly on civil aviation lines, then in the near future supersonic passenger aircrafts will fly under which the operating conditions for fuels, lubricants, and special liquids are considerably more complex, then in subsonic conditions. This is primarily associated with the sharply increasing temperature condition of the operation of the systems in supersonic aircraft. Therefore, on supersonic passenger aircrafts a more qualitative, and in a number of cases, completely new brands of fuels, lubricants, and special liquids will be used.

The second publication of the book is considerably revised and supplemented. The critical remarks made by the readers after publication in 1965 of the first book "Aviation Fuels, Lubricants, and Special Liquids" are considered in it. The book is also supplemented with new scientific data, which has appeared in the period from 1965 up to now.

P A R T   I

AVIATION FUELS

1

C H A P T E R   I

THE PRODUCTION OF PETROLEUM FUELS AND
THEIR CHEMICAL COMPOSITION

The basic source for obtaining fuels, of lubricants, and
also many special liquids is oil.

Oil got its name from the work "nafta," which in the language
of one of the peoples of Asia Minor meant "to ooze." Oil — this
is a combustible oily liquid frequently of a dark color, infrequently
light yellow or even colorless with a characteristic smell. Oil is
known from ancient times. It was used as a medicine, as an
illuminating material, as a cementing substance in construction, etc.
Up to the middle of the 19th Century oil was obtained by a primitive
method in very small quantities. With the onset of the beginning
of the 20th Century and with the further development of engine
construction the need for oil and oil products sharply grew, and
this gave an enormous push in the extraction and processing of oil.
Many of the most famous native and foreign chemists and engineers
worked in the area of the study and processing of oil. Such
scientists, as D. I. Mendeleyev, V. V. Markovnikov, V. G. Shukhov,
A. A. Letniy, A. M. Butlerov, N. D. Zelinskiy, I. M. Gubkin, S. S.
Nametkin, Engler, Schorlemmer, Maybern, and others introduced an
enormous contribution to the science of the chemistry of oil.

In 1964 the Soviet people noted the 100th anniversary of the native petroleum and gas industry. In oil reserves the USSR occupies first place in the world.

In 1970 our country planned to extract 350 million tons of oil. In the years of Soviet power the oil refining and petrochemical industry was turned into a forward looking branch of the national economy fitted out with the latest equipment.

1. The Composition of Oil

Oil is a complex mixture, consisting of a large number of chemical compounds and separate elements. The composition of oil includes hydrocarbons of various structures, organic and inorganic sulfur compounds, oxygen, nitrogen, dissolved and emulsified water, mechanical impurities, elemental sulfur, and some metals. On the average the composition of oil (by weight) is the following:

```
Hydrocarbons................................... 91—97%
Compounds of sulfur and free sulfur..........0,2—3,0%
Compounds of oxygen..........................0,2—1,5%
Compounds of nitrogen........................0,5—3,0%
Other compounds and elements.................0,1—0,5%
Water........................................0,05—0,50%
Mechanical impurities........................0,05—0,5%
```

The physicochemical properties of the hydrocarbons, and also the content of sulfurous, nitride, and oxygen compounds depend on the location of the oil. There are, for example, low-sulfur, sulfurous, naphthene, paraffinic oils and others.

Of all of the hydrocarbons in the composition of oil a relatively small part can be used as aviation fuel. Thus, to get aviation gasolines 20-25% of the hydrocarbons which have a boiling temperatures of 40-180°C are used; for some aviation kerosenes 35-40% of the hydrocarbons which have a boiling temperature of 150-280°C are used.

2. Obtaining Fuels

The basic methods of obtaining of fuels from oil are direct distillation and destructive processing.

Direct distillation is understood as obtaining the separate component parts from oil with the aid of subsequent or simultaneous vaporization of them with division of the vapors formed and subsequent condensation. This is the simplest and oldest method of processing oil. A line diagram of the installation for direct distillation of oil is shown in Fig. 1.
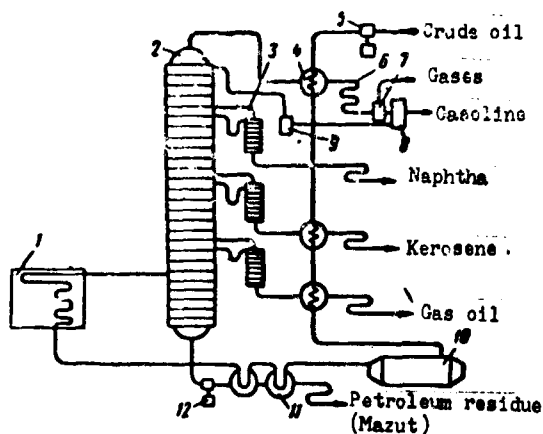
Fig. 1. Line diagram of a tubular installation with a one-time vaporization for the direct distillation of oil.

The oil with the aid of centrifugal pump *5* is supplied under pressure through three heat exchangers *4*, dirt separator *10* and mazut heat exchangers *11* and, heated to 170-175°, it enters tubular furnace *1*. Heated in the furnace to 330° and having partially evaporated, the oil enters fractionating column *2*, equipped with external stripping sections *3*. From the top of the column the benzine fraction is removed, and from the side stripping sections — the naptha, kerosene and gas oil fractions. The gasoline vapors are condensed and cooled in the heat exchanger and refrigerator *6*. Passing through gas separator *7*, the gasoline enters receiver *8*, from where a part of the gasoline is removed by pump *9* to irrigate the column. The remaining fractions passing through the heat

exchangers and refrigerators, are directed to the receivers. The petroleum residue from the bottom of the column is pumped by pump *12* through heat exchangers *11* and the refrigerator into receivers. There exist various structural designs for direct distillation installations.

With direct distillation liquid fuels are obtained in the quantities in which they are contained in the basic oil. This method does not satisfy the growing needs for fuels. Today methods have been developed for the destructive processing of oil and oil products which increase considerably the yield of fuels from oil.

Destructive processing is based on splitting the hydrocarbon molecules and it is the most widespread method of chemical processing of oil and oil products.

Splitting the high-molecular hydrocarbons which are found in the heavy fractions of oil, to get the lighter fractions (lower molecular weight) was studied already in the past century. In 1875-1878 A. A. Letniy published works, in which he showed that under the effect of high temperature the heavier hydrocarbons decompose into lighter ones. In 1891 V. G. Shukhov proposed the project of an industrial installation to obtain light hydrocarbons by means of the thermal decomposition of the heavier. This was the first in the world cracking installation project. The process of the thermal splitting of molecules received the name of cracking. The cracking process takes place according to the following scheme:

$$C_n H_m \rightarrow C_{n_1} H_{m_1} + C_{n_2} H_{m_2};$$

moreover

$$n_1 + n_2 = n \text{ and } m_1 + m_2 = m.$$

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The cracking of octadecane take place in the following manner:

$$C_{18}H_{38} \rightarrow C_9H_{20} + C_9H_{18};$$
$$t_{кип} = 317,5°C; \quad t_{кип} = 150°C; \quad t_{кип} = 146°C;$$
$$d_4^{20} = 0,787; \quad d_4^{20} = 0,718; \quad d_4^{20} = 0,729,$$
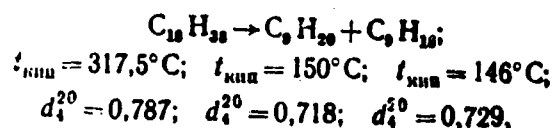
where d_4^{20} — the relationship of the density of the hydrocarbon at 20°C to the density of water at 4°C.

The cracking process can take place under the influence of only heat or under the influence of heat in the presence of a catalyst, which facilitates the direction of the reactions most advantageous for production. In the first case the cracking process is called *thermal*, in the second — *catalytic*. Both processes take place under airless conditions.

In the thermal cracking process hydrocarbons of a large molecular weight (petroleum residue, kerosine-gas oil fraction, etc.) are heated to a temperature of 450-500°C at a pressure of 45-50 kgf/cm^2. Under these conditions the hydrocarbons split forming lighter fractions (benzine, naptha).

During the thermal cracking process, as a rule, paraffin and unsaturated hydrocarbons of olefin (alkenes) and diolefin (alkadienes) orders which is one of the most characteristic distinctions of the thermal cracking process from other forms of oil processing.

Olefin and diolefin hydrocarbons of a chain structure have one (olefin) or two (diolefin) double bonds. The general formula for olefins — C_nH_{2n}, for diolefins — C_nH_{2n-2}. In view the presence of double bonds the hydrocarbons of these groups are more reaction prone and less chemically stable than paraffins, naphthenics, and the aromatic hydrocarbons. Olefin and diolefin hydrocarbons are capable of addition reactions, including oxidation. Therefore the presence of the hydrocarbons of these groups in aviation fuels is not permitted.

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Cracking gases are formed as by-products of the cracking process.

The catalytic cracking process is distinguished from the thermal process in that the parts of hydrocarbons of the raw material being processed are passed over a catalyst, i.e., a substance, which accelerates and directs the course of the reactions, and in this case the products obtained are more qualitative, than those obtained from thermal cracking. Today as a catalyst the most widely used are the aluminosilicates, which contain about 70-80% SiO_2, 10-18% Al_2O_3. To increase the catalytic effect of the aluminoscilicates oxides of iron, nickel, copper and other metals are also added to them.

In the presence of aluminosilicates splitting of the hydrocarbons begins at 300-350°C and flows intensively at 480-510°C. Cracking is accomplished at a pressure of 2-3 kgf/cm^2 or at atmospheric pressure.

Today there exist three basic industrial methods of catalytic cracking: with an immobile or mobile catalyst, and a powdered "fluid," or with a fluidized catalyst. A diagram of the cracking process with an immobile catalyst is shown in Fig. 2. The raw material for the cracking process is usually the kerosene, solar oil and gas oil fractions. The products of the catalytic cracking process are used as new materials for automobile and aviation fuels.

To obtain high-quality components for aviation fuels which improve the detonation chracteristics, volatility, density, and calorific value, the processes of reforming, hydrogenation, alkylation and others are used.

Reforming — this is a variety of the cracking process in which the structure of the hydrocarbon molecules is changed. The process consists of heating the fractions (benzine or kerosene) to a temperature of 500-520°C at a pressure of 50-70 kgf/cm^2. Under these conditions the napthenic and paraffin hydrocarbons turn into aromatic, isoparaffinic, and others.

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Drop of the blue gases into a tube
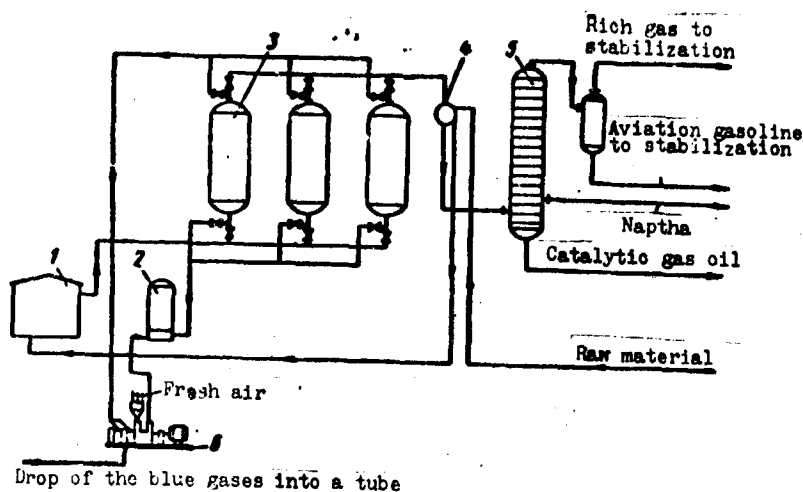
Fig. 2. Line diagram of the installation for the catalytic cracking process with an immobile catalyst: *1* — tubular furnace; *2* — air heater; *3* — reactors; *4* — heat exchanger; *5* — fractionating column; *6* — a turbocompressor.

During hydrogenation the addition of **hydrogen** to aromatic hydrocarbons takes place and they turn into napthenics, the addition of hydrogen to unsaturated hydrocarbons turns **them** into paraffin.

During alkylation alkyl radicals are joined to the molecules of hydrocarbons. As a result molecules with a determined structure are obtained which provides the required properties of the fuels.

3. Refining Fuels

Fuels obtained from oil contain chemical compounds which deteriorate their quality. Oxygen, sulfurous, nitride and others belong to such compounds. Furthermore fuels (especially in thermal cracking) can contain unsaturated hydrocarbons which considerably lower their chemical stability. To improve the properties of fuels they are subjected to refining by the following methods: sulphuric acid, alkali, bleaching earths, zinc chloride, sodium plumbite, hydrofining, and others. Depending on the quality of the basic raw material and the requirements for the fuel one or another refining method is used.

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Refining with sulphuric acid is used to remove a number of the unsaturated hydrocarbons, resinous, nitride, and sulfurous compounds. Refining with alkali is used to remove oxygen compounds, hydrogen sulfide, mercaptans, and also to remove sulphuric acid and the products of its interaction with the hydrocarbons.

Refining with bleaching earths in a steam phase consists of transmitting gasoline vapors through a layer of porous earth. The action of bleaching earth when refining cracking benzines is expressed in the acceleration and easing of the polymerization of unsaturated compounds.

Refining with zinc chloride is used to speed up the polymerization of unsaturated hydrocarbons and to remove mercaptans and hydrogen sulfide, and with sodium plumbite to remove mercaptans from the fuel.

Recently for more complete removal of sulfurous compounds from the fuel catalytic hydrofining is used. This process is accomplished in a hydrogen medium at a pressure of 10-70 at and a temperature of 390-420°C in the presence of an alumo-cobalt-molybdenum catalyst. Under these conditions hydrogenation of the sulfurous compounds takes place with the formation of hydrogen sulfide, and also oxygen nitrogen-containing compounds. Hydrofining is the most promising method for deep refining of aviation fuels.

4. The Factional and Chemical
Composition of Fuels

A fraction is called the part (group) of the hydrocarbons that boils off at a determined temperature interval. All hydrocarbons which make up oil and which boil off at temperatures of 40-200°C are called the benzine fraction.

The hydrocarbons which boil off at temperatures of 150-300°C are called the kerosene fraction. In turn the benzine or kerosene fractions can be divided in narrower fractions, i.e., the groups of hydrocarbons which boil off in narrower temperature limits. For

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example, the kerosene fraction can be divided into 50-degree fractions and the composition of kerosene is analyzed according to the number of hydrocarbons in each fraction.

With respect to the factional composition, aviation fuels can be divided into the following groups: gasolines — boiling out limits 40-200°C, kerosenes — 150-300°C, ligroines — 150-250°C, fuels of wide fractions — 60-300°C, heavy kerosenes — 200-350°C.

The aviation fuels obtained from oil consist of hydrocarbons (approximately 98.5%) and nonhydrocarbon impurities (approximately 1.5%). Despite the relatively small amount of nonhydrocarbon impurities, they, as we are convinced of further, exert great influence on the operating properties of aviation fuels. The main car.ters of energy and some operating properties of fuels are the hydrocarbons. The constant attempt to increase in the weight and volumetric heat of combustion, to improve the combustion properties, and the low-temperature and high-temperature properties of fuels led to the necessity for deep study of the chemical structure of hydrocarbons as well as to the development of such technological methods of fuel production, when the necessary hydrocarbons are included in their composition. The hydrocarbons in the composition of fuels are divided into the following groups.

Paraffins, or unsaturated hydrocarbons (alkanes). The molecules of these hydrocarbons can have a various number of carbon atoms joined only in single bonds and forming open chains. The general empirical formula of this group of hydrocarbons is C_nH_{2n+2}. The paraffins whose molecules have the nonbranching chains of carbon atoms, bear the name of standard paraffins (n-paraffins, n-alkanes). Besides the standard paraffin, isomeric hydrocarbons — isoparaffins (isoalkanes) are found in fuels.

Isomery is one of the reasons for the variety of organic compounds, since with an increase in the number of atoms in a molecule the number of possible isomers increases rapidly. Thus, for the hydrocarbon C_5H_{12} three isomers are possible, for the

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hydrocarbon $C_8H_8 - 18$, and for $C_{10}H_{22} - 75$. Aviation fuels are made up basically of liquid paraffin hydrocarbons with the number of carbon atoms in a molecule from 5 to 15 both in the normal, and in the isomeric structure. In light fuels the gaseous hydrocarbons: methane (CH_4), ethane (C_2H_5), propane (C_3H_8) and butane (C_4H_{10}) can be found in the dissolved state in insignificant quantities. In heavier fuels solid paraffin hydrocarbons with the number of carbon atoms more than 15 can be found in the dissolved state. Table 1 gives the characteristic properties of the paraffin hydrocarbons that are part of the fuels.

Table 1.   Characteristics of paraffin hydrocarbons

Hydrocarbons	Empirical formula	Structure	Density, g/cm³	Temperature, °C	
				melting	boiling
Pentane	C_5H_{12}	$CH_3-(CH_2)_3-CH_3$	0,626	—129,7	36,1
Isopentane (2-methylbutane)	C_5H_{12}	CH_3 $CH_3-CH-CH_2-CH_3$	0,260	—159,9	27,9
Hexane	C_6H_{14}	$CH_3-(CH_2)_4-CH_3$	0,659	—95,3	68,7
Isohexanes 2-methylpentane	C_6H_{14}	CH_3 $CH_3-CH-(CH_2)_2-CH_3$	0,653	—153,7	60,3
3-methylpentane	C_6H_{14}	CH_3 $CH_3-CH_2-CH-CH_3-CH_3$	0,664	—118,0	63,8
2, 2-dimethylbutane	C_6H_{14}	CH_3 $CH_3-C-CH_2-CH_3$ CH_3	0,649	—99,7	49,7
2, 3-dimethylbutane	C_6H_{14}	CH_3 CH_3 $CH_3-CH-CH-CH_3$	0,662	—128,4	58,0
Heptane	C_7H_{16}	$CH_3-(CH_2)_5-CH_3$	0,684	—90,6	98,4
Isoheptanes 2-methylhexane	C_7H_{16}	CH_3 $CH_3-CH-(CH_2)_3-CH_3$	0,679	—118,3	90,1
3-methylhexane	C_7H_{16}	CH_3 $CH_3-CH_2-CH-(CH_2)_2-CH_3$	0,687	—119,4	91,9

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Table 1. (Cont'd)

Hydrocarbons	Empirical formula	Structure	Density, g/cm³	Temperature, °C	
				melting	boiling
2, 2-dimethylpentane	C_7H_{16}	CH_3 $CH_3-C-(CH_2)_2-CH_3$ CH_3	0,674	—123,8	79,2
2, 3-dimethylpentane	C_7H_{16}	CH_3 CH_3 $CH_3-CH-CH-CH_2-CH_3$	0,695	—	89,8
2, 2, 3-trimethylbutane	C_7H_{16}	CH_3 CH_3 $CH_3-C-CH-CH_3$ CH_3	0,690	—25	80,9
3-ethylpentane	C_7H_{16}	$CH_3-CH_2-CH-CH_2-CH_3$ C_2H_5	0,698	—118,6	93,5

The paraffin (alkane) hydrocarbons in fuels have good chemical stability during storage, low melting and boiling temperatures, the greatest heat of combustion be weight and the lowest density. The volumetric heat of combustion in connection with this for paraffins is less than in other groups of hydrocarbons.

The paraffin hydrocarbons of a normal structure unlike the hydrocarbons of an isomeric structure have unsatisfactory characteristics of combustion in piston engines with a spark ignition (low octane numbers).

Napthenic hydrocarbons (cyclanes, cycloparaffins) have a ring structure molecule. The ring is composed of atoms of carbon, all free the valences of which are substituted with atoms by hydrogen. A typical representative of the napthenic hydrocarbons is cyclopentane

CH_2
H_2C CH_2
H_2C-CH_2

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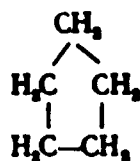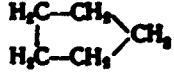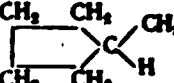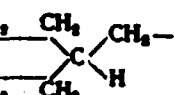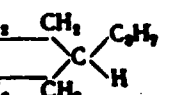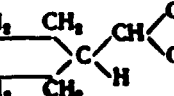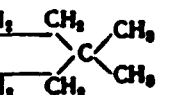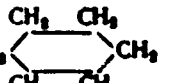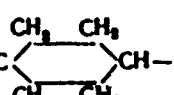
The general structural formula of napthenic hydrocarbons consisting of one ring is C_nH_{2n}.

Naphthenic hydrocarbons can consist of several condensed rings or of a ring with associated paraffin chains of a different structure. This explains the large variety of napthenic hydrocarbons.

More frequently than anything, monocyclic naphthenic hydrocarbons which possess a naphthenic ring with lateral chains (alkano-cyclane hydrocarbons) are in fuels. Table 2 gives the characteristic properties of naphthenic hydrocarbons.

Table 2. Characteristics of naphthenic hydrocarbons

Hydrocarbons	Empirical formula	Structure	Density, g/cm^3	Temperature, $^{\circ}C$	
				melting	boiling
Cyclopentane	C_5H_{10}		0,745	—93,8	49,3
Methylcyclopentane	C_6H_{12}		0,749	—142,5	71,8
Ethylcyclopentane	C_7H_{14}		0,767	—138,4	103,5
Propylcyclopentane	C_8H_{16}		0,776	—117,3	130,9
Ispropylcyclopentane	C_8H_{16}		0,777	—111,4	126,4
1, 1, 3-trimetyloyclo-pentane	C_8H_{16}		0,748	—142,4	104,9
Cyclohexane	C_6H_{12}		0,779	+6,5	80,8
Methylcyclohexane	C_7H_{14}		0,769	—126,6	100,9

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Naphthenic hydrocarbons, as a rule, are present in medium and heavy fractions and have a high chemical stability. In comparison with paraffin hydrocarbons they possess a greater density, a higher boiling temperature, and a somewhat less gravimetric heat of combustion.

These compounds possessing the optimum properties are more preferable today for aviation fuels, than other groups of hydrocarbons.

Aromatic hydrocarbons consist of one or several benzene rings, and also of benzene rings with associated lateral paraffin chains.
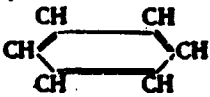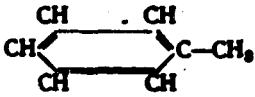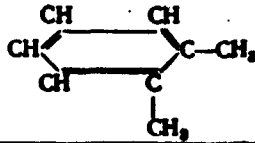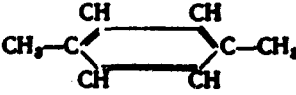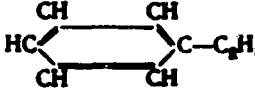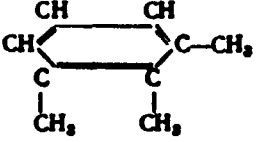
The first hydrocarbon of the aromatic series is benzene, for which F. Kekule in 1865 offered the following structural formula:

$$
\begin{array}{c}
\text{CH} \\
\text{CH} \diagup \text{CH} \\
\text{CH} \diagdown \text{CH} \\
\text{CH}
\end{array}
$$
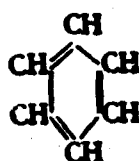
The double bonds of the benzene ring do not have a strictly fixed position as in other hydrocarbons, but they continuously and spontaneously change places with the singles. In connection with this the structure of the benzene ring proposed by Kekule, should be taken as arbitrary. The general structural formula of monocyclic aromatic hydrocarbons is C_nH_{2n-6}.

Aromatic hydrocarbons have in comparison with paraffins and naphthenics a higher temperature and density, and therefore, also a larger volumetric heat of combustion. They are somewhat more reaction prone than the paraffins and naphthenes. Upon combustion of the aromatic hydrocarbons considerably more incomplete combustion products (carbon) are formed than during the combustion of paraffins and of naphthenes. Furthermore, they are hygroscopic. The characteristics of the aromatic hydrocarbons are given in Table 3.

Table 3. Characteristics of aromatic hydrocarbons

Hydrocarbons	Empirical formula	Structure	Density, g/cm^3	Temperature, $^\circ C$	
				melting	Boiling
Benzene	C_6H_6		0,879	+5,5	80,1
Methylbenzene (toluene)	C_7H_8		0,867	—95,0	110,6
1, 2-dimethylbenzene (O-xyloyl	C_8H_{10}		0,880	—25,2	144,4
1, 4-dimethylbenzene (P-xycyl)	C_8H_{10}		0,861	+13,3	138,4
Ethylbenzene	C_8H_{10}		0,867	—95,0	136,2
1, 2, 3-trimethyl-benzene (oumol)	C_9H_{12}		0,894	—25,4	171,1

Recently the volumetric heat of combustion has acquired an ever greater value for aviation fuels. It is possible to substantially increase the volumetric heat of combustion, only by including in the composition of the fuel a considerable quantity of specially selected aromatic hydrocarbons, and in this case the basic operational properties of the fuel should not deteriorate.

Sulfurous compounds. In aviation fuels in a small quantity (not more than 0.2% of the weight), but always, there are free sulfur and sulfurous compounds. The most widespread sulfur compounds in fuels are the mercaptans (RSH), the sulphides (R-S-R), disulfides (R-S-S-R), thiophanes

$$\begin{array}{cc} CH_2-CH_2 \\ | \quad\quad | \\ CH_2 \quad CH_2 \\ \diagdown_S \diagup \end{array}$$

and thiophenes

$$\begin{array}{cc} CH-CH \\ \| \quad\quad \| \\ CH \quad CH. \\ \diagdown_S \diagup \end{array}$$
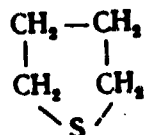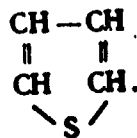
Free sulfur in fuel is found in the dissolved state. The quantity of free sulfur is strictly limited because it is an active corrosive element. The typical group composition of the sulphureous compounds in jet fuel is the following:

General content of sulfur in fuel, % by weight.....0.2

Composition of sulfurous compounds, relative % in a conversion to sulfur:

```
mercaptans................................. 16
aliphatic sulfides......................... 44
aromatic sulfides..........................  7
disulfides................................. 10
elementary sulfur..........................  2
residual compounds......................... 21
```

The given composition of the sulfurous compounds depends on the oil deposit, the technology of production, and the refining of the fuel.

Among the sulfurous compounds the most reaction prone are the mercaptans (RSH), and the least stable when subjected to the processes of bodying and decay, are the mercaptans and disulfides.

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Despite the fact that sulfurous compounds are found in fuels in small quantities, they exert at elevated temperatures a large effect on the stability of the fuels and on the corrosion and antiwear properties.

Oxygen compounds. Unlike other nonhydrocarbon impurities oxygen compounds constantly accumulate in fuel due to the oxidation of unstable hydrocarbons, sulfurous, nitrides, and primary oxygen compounds. The quality of the fuels is judged according to the speed of the oxidation processes. The oxygen compounds contained in fuels can be divided into organic acids, simple and complex eithers, and tar-asphalt substances.

The organic acids (R-COOH) present in fuels most frequently are naphthenic; their molecules contain naphthene radicals basically cyclopentanes, therefore the general formula of the acids can be written in the form $C_nH_{2n-1}COOH$. At the same time aliphatic carbonaceous acids are found, in the molecule of which R — radical of hydrocarbon having a valuable structure.

The tar-asphalt substances are the products of the deep oxidation of organic acids, eithers, and alcohols at increased temperatures and due to the catalytic effect of metals.

Nitride compounds in aviation fuels, especially in light fuels are very rare because their basic part concentrates in the heavy fractions of oil. This, as a rule, is the heterocyclic compounds with an atom of nitrogen in one or in several rings. Most frequently the homologues of pyridine (1), quinoline (2), a pyrrole (3), indole (4) are found:
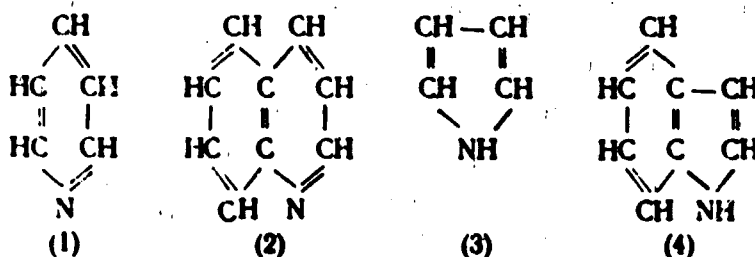
In aviation fuels the nitrogen content constitutes less than 0.1%. But even such small quantities have an effect on the operational properties of the fuels.

The composition of the solid phase isolated from the fuels, and also in the composition of carbon deposits, deposits on burners reveals a large quantity of nitride compounds. This bears witness to the fact that nitride compounds serve as a material for the formation of deposits, carbon deposits, resins, etc.

Mineral impurities and water. The ash content in aviation fuels does not exceed 0.003% by weight. Ash is formed as a result of soil falling into the fuel, the products of corrosion of storage tanks and pipelines, and the products of wear of the parts of the fuel apparatus. The quantity of mineral impurities increases sharply with a breakdown in the rules of storage and transportation of the fuels, and also with the increase in the corrosion and wear of the parts of the fuel apparatus at elevated temperatures.

Water in fuel can be found in the dissolved state and in the form of an emulsion. The overall content of water in fuels depends upon the temperature, atmospheric pressure, humidity, and also the conditions of storage, transport, and of the pumping of the fuels. The overall content of water in fuels fluctuates over wide limits from 0.001 to 0.1%. Water exerts a large effect on the filterability of fuels and on their corrosive properties.

C H A P T E R   II

METHODS OF EVALUATING THE PHYSICOCHEMICAL
PROPERTIES OF AVIATION FUELS

1. The Requirements Set Forth for
Aviation Fuels

Modern fuels for civil aviation must satisfy a number of
requirements connected with economy, reliability, and longevity of
work of aviation technology. Reliable and long-lasting work of an
aircraft is provided for when the fuels being used:

have an optimum factional composition, giving a steady
combustion process under all operating conditions of the engine and
which does not cause the formation of vapor plugs in the fuel system
during high-altitude flights;

do not exert a harmful effect on the parts of the fuel system
of an aircraft and engine;

provide for reliable operation of the engines over a wide range
of external conditions: temperatures, pressures, humidity, etc.;

do not change their composition and properties during prolonged
storage.

The economical operation of an aircraft is possible if the
fuels being used have a low cost, high heat of combustion and high
density, the chemical and group composition which provide for the

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most complete combustion process and which vaporize little during
high-altitude flights and prolonged storage.

Furthermore, the fuels should be safe and not exert a harmful
effect on a man. Practical fuels, as a rule, do not possess the
whole complex of desirable properties.

A GOST is developed for each type of fuel used in civil aviation,
in which the basic physicochemical indexes of the quality of the
fuel are enumerated and the permissible limits of their values are
given. A GOST is the only document, according to which the quality
of the fuel being used in the operational subdivisions of civil
aviation is evaluated.

Each batch of fuel obtained in an oil-refining plant undergoes
a laboratory analysis — to determine those quality indexes which
are described in the GOST. If the values of the indexes determined
under laboratory conditions correspond to the values described in
the GOST, the fuel is considered fit and leaves for the airports
of civil aviation.

2. The Basic Physicochemical Properties
of Fuels and Methods of
Evaluating Them

. All the physicochemical properties of fuels can be conditionally
divided in operational and control. The fuel is judged according
to its operational properties on the possibility of using it in
this or that engine, under these or other conditions. It is judged
according to the control properties on the identity of batches of
fuel. Furthermore, the control indexes are a necessary addition to
the operational properties of the fuel.

Operational properties. As fuels for modern aircraft we
are attempting to use substances consisting of elements of their
compounds with the greatest heat of combustion because the higher
the heat of combustion of the fuels, the less their specific
consumption and the longer the range of an aircraft.

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The heat of combı tion — one of the most important character-
istics, making it possible to evaluate the energy capabilities of
the fuel.

The heat of combustion of fuels is called the quantity of
thermal energy in kilocalories given off when 1 kg or 1 *l* of fuel
is burned in an atmosphere of oxygen or air. In connection with
this the heat of combustion can be expressed in two ways: in a unit
of mass and a unit of volume. The heat of combustion of fuels is
determined by an experimental method according to GOST 5080-55, by
burning 0.5-0.6 g of fuel in a calorimeter in an atmosphere of
oxygen and then calculating the amount of thermal energy with
respect to the heating of water in the calorimeter (Fig. 3).
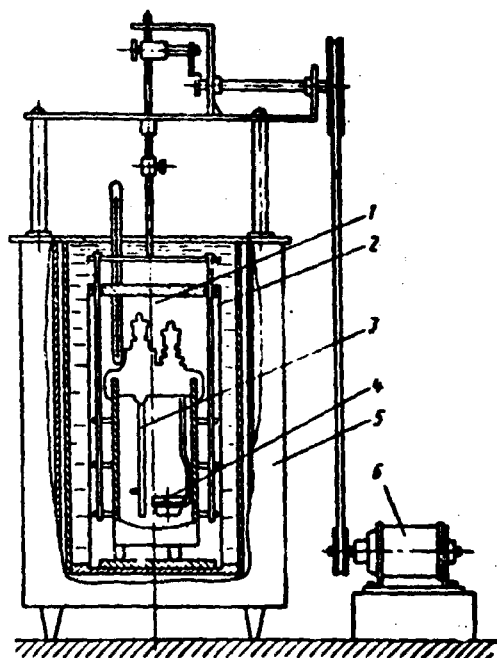
Fig. 3. The diagram of a calori-
metric device for determining the
heat of combustion of a fuel: *1* —
chamber; *2* — mixer; *3* — igniter;
4 — crucible with the fuel to be
tested; *5* — body of the calori-
meter; *6* — electric motor.

Two values of the mass heat of combustion are distinguished:
the highest and the lowest. The highest heat of combustion is called
the amount of heat energy which is given off upon complete combustion
of a unit of mass of fuel at standard atmospheric pressure and
cooling of the products of combustion down to 25°C. In this instance
the heat is considered that was given off upon condensation of the
water vapors found in the products of combustion.

In an engine the heat of condensation of water is not used because water is ejected together with the products of combustion in the form of steam. Therefore in technology not the highest, but the lowest heat of combustion is used which does not include the heat of condensation of water.

Along with determining the heat of combustion of fuel by means of burning it directly in a calorimeter there exists the method of calculating the heat of combustion using an empirical formula. The heat of combustion of a fuel can be ca.~culated approximately using the formula of D. I. Mendeleyev

$$Q_\text{в} = 81C + 300H -$$
$$- 26(O - S);$$
$$Q_\text{н} = 81C + 246H -$$
$$- 26(O - S) - 6W,$$

where $Q_\text{в}$ — the highest heat of combustion of a fuel, kcal/kg; $Q_\text{н}$ — the lowest heat of combustion of fuel, kcal/kg; C — the carbon content in a fuel, %; H — the hydrogen content in a fuel, %; O — the oxygen content in a fuel, %; S — the sulfur content in a fuel, %; W — the water content in a fuel, %.

To evaluate the heat of combustion of a fuel a number of foreign countries use the coefficient of calorific value. The coefficient of calorific value is the product of the density of a fuel, expressed in degrees API, to the aniline point in the degrees Fahrenheit. To translate the degrees API into units of density the following formula is used

$$d_4^{20} = \frac{141,5}{131,5 + {}^\circ API} \cdot$$

The heat of combustion is indirectly controlled by the method of determining the coefficient of calorific value.

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There exists a determined relation between the heat of combustion and the coefficient of calorific value of a fuel:

Heat of combustion, kcal/kg	Coefficient of calorific value
10 170	4 500
10 280	6 000
10 440	8 250
10 500	9 000

For native kerosenes according to the data of N. A. Ragozin the coefficient of calorific value fluctuates within the limits of from 5590 to 5850.

Since the methods of determining the density and the aniline point are simpler than the direct determination of the heat of combustion, then the coefficient of calorific value is a more convenient (from the point of view of the method of determination) index, especially for the control definitions under the conditions of operational laboratories. There also exists a number of other approximate methods of calculating the heat of combustion of fuel, described in special literature.

The heat of combustion of hydrocarbon fuels depends on the chemical composition and the structure of the individual hydrocarbons, which enter the composition of the fuel, and for the hydrocarbons of the various groups it is found within the limits 9500-10,500 kcal/kg. Table 4 gives the values of the heat of combustion for a unit of mass and of volume for elements which possess the greatest heat of combustion in comparison with the remaining elements of the periodic system.

As seen from Table 4, only hydrogen, beryllium, and boron according to the mass heat of combustion exceed hydrocarbons, therefore the selection of fuels with a higher heat of combustion is very limited.

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Table 4. The highest heat of combustion of some elements

Element	Symbol	Density, g/cm^3	Heat of combustion		State of the oxide
			kcal/kg	kcal/l	
Hydrogen*.....................	H	0,07	28 900	2 110	Gaseous
Beryllium....................	Be	1,85	15 000	27 750	Solid
Boron........................	B	2,30	13 956	31 400	The same
Lithium......................	Li	0,50	10 300	5 450	" "
Carbon (amorphous)...........	C	1,80—2,10	7 840	15 700	Gaseous
Aluminum.....................	Al	2,70	7 290	19 700	Solid
Silicon......................	Si	2,00	7 160	14 350	The same
Magnesium....................	Mg	1,43	6 000	8 550	" "

* For hydrogen the lowest heat of combustion.

The heat of combustion of fuel depends on the ratio of carbon and hydrogen in the molecules of individual hydrocarbons. The hydrogen contained in the fuel the higher the heat of combustion. The paraffin hydrocarbons C_nH_{2n+2} have the greatest mass heat of combustion. They contain more hydrogen in comparison with napthenes C_nH_{2n} by approximately 1.1 times, and in comparison with aromatic hydrocarbons C_nH_{2n-6} — by 1.5-2 times. However one should have in mind that with the transition from paraffin hydrocarbons to naphthenic and aromatic the density of the hydrocarbons increases; this leads to an increase in the volumetric heat of combustion.

The *volatility* of a fuel is one of the main operational characteristics because it influences the processes of carburetion and combustion, the losses of fuel in high-altitude flights, and the possibility of the formation of a vapor plug in fuel lines. The volatility of a liquid is called its capacity to change over into the gaseous state. It is judged mainly according to two indexes: the factional composition and the pressure of the saturated vapors.

Hydrocarbon fuel is a liquid of complex composition, consisting of a large quantity of individual hydrocarbons. Such a liquid does not have a fixed boiling temperature; the process of boiling occurs in a certain range of temperatures. It is possible to characterize

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the volatility of liquids of a complex composition by the fractional
composition, i.e., by the limiting temperatures of boiling out certain
volumetric segments (fractions). The characteristic points of the
factional composition are usually considered the temperature of the
beginning of boiling, the temperature of boiling out 10, 50, 90%
of the, volume of fuel, and the temperature of the end of boiling.
The factional composition of. a fuel is determined according to
GOST 2177-59 under laboratory conditions on a standard device, a
diagram of which is shown in Fig. 4.
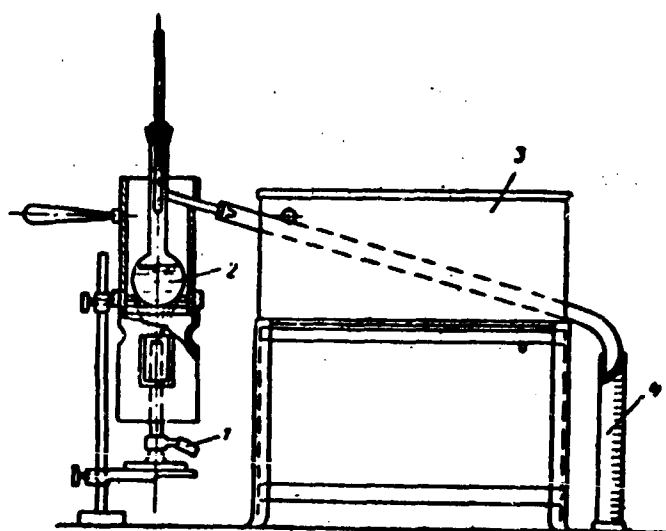
Fig. 4. The diagram of
a device for determining
the factional composition
of a fuel.

A quantity of 100 cm^3 of the fuel to be tested is poured
into flash 2 and is heated on burner 1. The fuel vapors passing
through refrigerator 3 are condensed and flow into receiving measuring
cylinder 4. The temperature is noted on the thermometer at which
the first drop falls into the measuring cylinder (the temperature
of the beginning of boiling), and further the temperatures at which
the determined percentage of condensate (10, 20, 30%, etc.) is
gathered in the measuring cylinder. The temperature of the end
of boiling is accepted as the temperature where 97.5-98% of the
fuel has boiled out.

The results of the test can be presented in the form of a
graph which makes it possible to compare fuels of a different
factional composition (Fig. 5) between themselves.
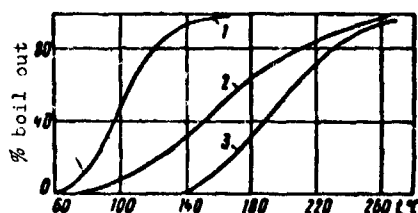
Fig. 5. Graph of the factional composition
of aviation fuels: *1* — aviation gasoline; *2* —
wide fraction type fuel; *3* — aviation kero-
sene.

Upon vaporization of a liquid in a closed vessel the process
of condensation which is the opposite of vaporization takes place
simultaneously. The higher the pressure of the vapors over the
liquid, the more intensive the process of condensation. Upon reaching
a certain pressure dynamic equilibrium approaches: the number of the
molecules leaving the surface of a liquid is equal to the number
of molecules returning into the liquid. Such a pressure is called
the pressure of saturated vapor. It strongly depends on the
temperature (Fig. 6). As seen from the given graph, the pressure
of the saturated steams of fuels changes more considerably at high
temperatures.
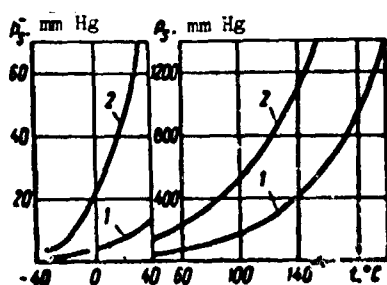
Fig. 6. Dependence of the pressure of the
saturated vapors of jet fuels on the tempera-
ture at a ratio of the liquid and vapor phases
of 1:4: *1* — aviation kerosene; *2* — wide
fraction type fuel.

For the liquids which are complex mixtures, the pressure of the
saturated vapors depends upon the ratio of the volumes of the vapor
and liquid phases. Figure 7 gives a graph of the dependence of the
pressure of the saturated vapors of aviation gasoline on the ratio

of the liquid and steam phases at temperatures of 0°, 20°, and 50°.
With an increase in the volume of the liquid phase of 5 times, the
pressure of the saturated vapors at a temperature of 0°C increases
approximately 3-3.5 times, and at a temperature of 50°C — 2-2.5 times.
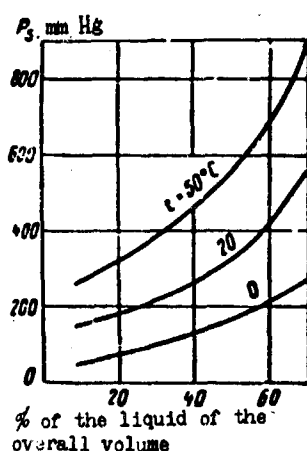
Fig. 7. Dependence of the pressure of the
saturated vapors of gasoline on the ratio
of the liquid and steam phases.

To determine the pressure of the saturated vapors under
laboratory conditions there exist two methods: GOST 1756-52 and
GOST 6668-53.

The pressure of the saturated vapors of fuels according to
GOST 1756-52 is determined at a temperature of 38°C and a ratio of
the vapor and liquid phases of 4:1 in the instrument, a diagram of
which is shown in Fig. 8. The instrument is a steel bomb consisting
of two chambers, moreover the volume of the lower is 4 times less
than the volume of the upper. During testing the lower chamber is
filled with the experimental fuel and the upper chamber, equipped
with a manometer is screwed onto it. The assembled instrument is
immersed in a liquid bath in which a constant temperature is
maintained. After the readings of the manometer stop changing, the
last reading of the manometer is taken and, entering a correction
on the change in pressure of the air due to the temperature, the
pressure of the saturated vapors of the fuel is obtained.
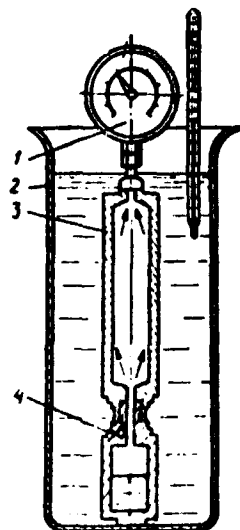
Fig. 8. Diagram of the instrument for determining the pressure of saturated vapors according to GOST 1756-52: *1* — manometer; *2* — tank with water; *3* — upper chamber; *4* — lower chamber.

Determination of the pressure of the saturated vapors according to GOST 6668-53 (the Valyavskiy-Budarov method) is accomplished in a special instrument (Fig. 9).
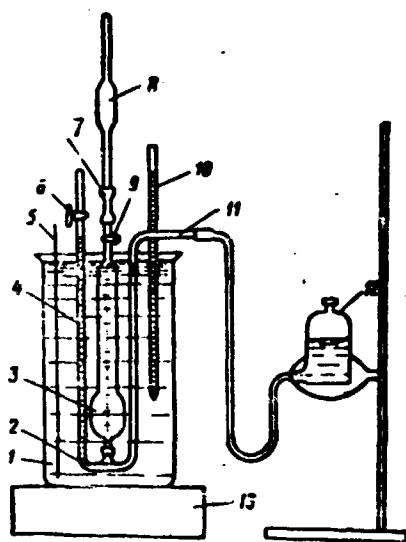
Fig. 9. Diagram of the instrument for determining the pressure of saturated vapors according to GOST 6668-53: *1* — vessel with water; *2* — T-piece; *3* — buret; *4* — barometric tube; *5* — mixer; *6* — valve; *7* — connecting tube; *8* — pipette; *9* — valve; *10* — thermometer; *11* — siphon tube; *12* — equalizing flask; *13* — electric heater.

The pressure of the saturated vapors is determined according to the increase in the volume of the vapor-air mixture after fuel evaporation in a buret at a constant pressure and ratio of the liquid and vapor phases of 1:1.

Determination is accomplished in the following manner: equalizing flask 12 is filled with water and the instrument is checked for airtightness. A temperature of 38°C is established in the vessel. Valves 6 and 9 are opened and buret 3 is filled with water, lifting equalizing flask 12. Having shut valve 9, the flask is sunk to such a level, at which the required volume of air should remain in the buret. Slowly opening valve 9, the water is poured from the buret and air is sucked in. The air is maintained at a temperature of 38 ± 0.1°C for 5 min, and the valve is closed. With the aid of tube 7 pipette 8 with the fuel to be tested is connected to the instrument. The equalizing flask is sunk to the proposed level after expansion of the mixture and, opening a valve 9, fuel is poured from the pipette into the buret and the valve is shut. The equalizing flask is installed so that the level of the liquid in the barometric tube is at the same height as the level of the fuel in the buret; it is held 5 min, whereupon the volume of the steam phase of the fuel in the buret on the upper meniscus is read.

The pressure of the saturated vapors of the tested fuel is calculated according to the formula

$$p_s = \frac{V_2 - V_1}{V_1} (p_{\text{атм}} - 49.7).$$

where p_s — the pressure of the saturated vapors of the fuel, mm Hg; V_1 — the initial volume of air (before fuel evaporation), ml; V_2 — the volume of the vapor-air mixture (after fuel evaporation), ml; $p_{\text{атм}}$ — atmospheric pressure, mm Hg; 49.7 — the pressure of the saturated water vapors in the buret at a temperature of 38°C, in mm Hg.

The characteristics of the volatility of fuels are approximate indexes because they are obtained under conditions of static varporization. For a more complete evaluation of the volatility of a fuel it is necessary to have the characteristics, obtained under dynamic conditions of vaporization, i.e., when the fuel is found in the form of

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droplets moving in a stream of air. However today the method of determining the volatility of a fuel under dynamic conditions of vaporization has still not been developed.

Viscosity — the property of a liquid to show a resistance during the movement of one of its parts relative to another. In other words, viscosity is the characteristic of interior fraction between the particles of the liquid. Dynamic and kinematic viscosity are distinguished.

Dynamic viscosity is called the resistance, appearing on a unit of area of the friction layers of a liquid with the transverse gradient of speed equal to one.

The coefficient of dynamic viscosity η is determined by equation

$$\eta = \frac{F}{S\frac{\Delta v}{\Delta l}} = \frac{F\,\Delta l}{S\,\Delta v},$$

where F — the force of resistance, N; S — the area of the layer, m^2; $\frac{\Delta v}{\Delta l}$ — the transverse gradient of speed, s^{-1}.

A unit of dynamic viscosity in the SI system is taken as the viscosity at which a force of 1 N acts at a transverse gradient s^{-1} on 1 m^2 layer of a liquid. The dimensions of dynamic viscosity — $N \cdot s/m^2$ or $kg/m \cdot s$. In technology the unit of measurement of the dynamic viscosity used is the poise (pz), moreover 1 pz = 0.1 N × × s/m^2.

The kinematic viscosity is called the dynamic viscosity exerted on a unit of density of a liquid:

$$v = \frac{\eta}{\rho},$$

where v — the coefficient of kinematic viscosity, m^2/s; η — the coefficient of dynamic viscosity, $kg/m \cdot s$; ρ — density, kg/m^3.

In technology the unit of measurement of kinematic viscosity used is the stoke (St), moreover 1 St = 1 cm^2/s = 10^{-4} m^2/s, and a unit 100 times less than a stoke — a centistoke (cSt); 1 cSt = = 0.01 cm^2/s = 10^{-6} m^2/s.

Water has a viscosity of 1 cSt at 20.2°C.

Measurement of the kinematic viscosity is accomplished under laboratory conditions using a capillary viscosimeter according to GOST 33-53 (Fig. 10). The viscosity is determined according to the time of discharge of the liquid from the phial of the viscosimeter between graduation lines a and δ through the capillary, the diameter of which is selected depending on the viscosity of the liquid being tested.
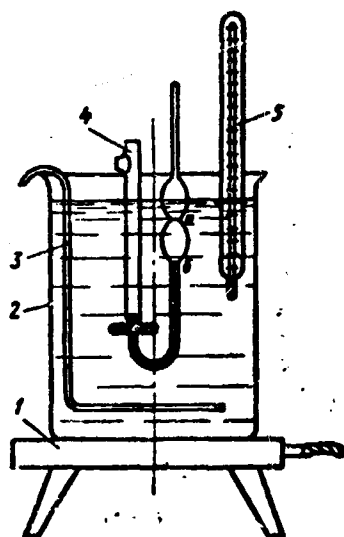
Fig. 10. Diagram of an instrument for determining the kinematic viscosity: 1 — electric heater; 2 — vessel with water; 3 — mixer; 4 — capillary viscosimeter; 5 — thermometer.

The viscosity of the hydrocarbons, in the composition of fuels changes, considerably with a change in the temperature. With an increase in temperature the viscosity decreases. The viscosity of gasolines is so small, that it practically does not have an effect on the operational characteristics of the gasoline systems of

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aircraft. The viscosity of kerosenes has a substantial effect on a number of important operational characteristics of the fuel system of aircraft and on the processes of carburetion and combustion in an engine.

Stability. Under fuel stability we understand its capacity to retain unchanged its physicochemical properties under conditions of storage, transport, servicing, and circulation through the fuel system of an aircraft. All petroleum fuels are unstable. The instability is manifested in that their component parts (hydrocarbons, sulfurous, oxygen, and nitride compounds) oxidize, polymerize, and condense. The rate of the processes of oxidation, polymerization, and condensation traction depend on the quality of the fuel and on external conditions.

These processes are most strongly accelerated by temperatures, catalysts, oxygen, light, etc. Evaluation of the stability of fuels can be accomplished both according to the rate of the oxidizing processes, and according to the quantity of products formed, oxidation, polymerization, condensation.

Today evaluation of the stability of fuels is accomplished according to the following indicators: from the quantity of actual resins, the size of the induction period, the indicators of thermal stability. Indirect indicators of stability are the quantity in a fuel of unsaturated hydrocarbons, organic acids, sulfur, and sulfurous compounds. These impurities considerably speed up the oxidizing, polymerization, and condensation processes in a fuel.

Actual resins are called the products, which remain in the form of a solid or semifluid residue in a glass beaker after the rapid and complete evaporation of fuel from it. In other words, these are resins, that are found in fuel in a dissolved state, and also partially formed for the time of conducting the experiment. To determine the quantity of actual resins under laboratory conditions there exist two methods: according to GOST 1567-56 and according to GOST 8489-58.

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A special heated oil bath (Fig. 11) is used when calculating according to the first method.
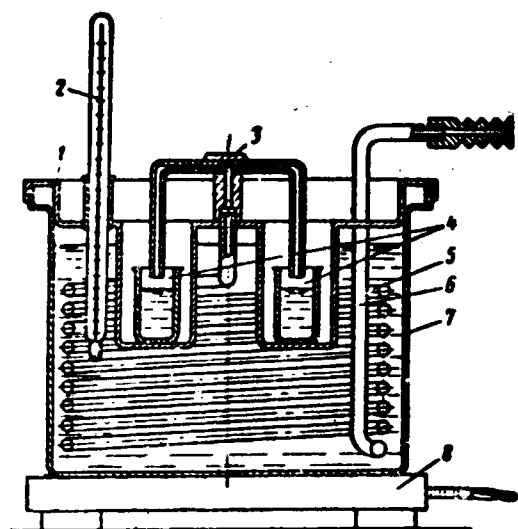
Fig. 11. Diagram of an instrument for determining the actual resins according to GOST 1567-56: *1* — cover; *2* — thermometer; *3* — T-pipe of the air supply; *4* — beakers with the fuel being tested; *5* — containers for mounting the beakers; *6* — air supply coil; *7* — housing of the heated oil bath; *8* — electric heater.

The test is conducted in the following manner: into thoroughly washed, dried, and suspended beakers 25 m*l* of the fuel being tested is measured off and the beakers are placed into the containers of the bath, heated to a specified temperature (for gasoline — 150°C, for kerosenes — 180°C). The supply of air in the beakers is turned on and gradually the rate of supply is brought up to 55 *l*/min. After complete evaporation of fuel and cooling the beakers are weighed. Then the quantity of actual resins is determined in milligrams per 100 m*l* of fuel using the formula

$$X = \frac{(G_2 - G_1)\,100}{25},$$

where X — the quantity of actual resins, mg/100 ml of fuel; G_1 — the weight of a clean dry beaker, mg; G_2 — the weight of the beaker with resins, mg.

To determine the quantity of actual resins according to GOST 8489-58 (the Budarov method) an instrument, the diagram of which is shown in Fig. 12 is used. Using a measuring cylinder, distilled water is measured off and poured into beakers for water (in testing

gasoline — 25 ml, in testing kerosenes — 35 ml). A quantity of 25 ml of gasoline or 30 ml of kerosene are measured off and poured into beakers which are placed into the containers of the bath, heated to a specified temperature (for gasolines — 160°C, for kerosenes — 180°C). Evaporation is accomplished under a stream of water vapor. After complete evaporation of the fuel the beakers are cooled and weighed, then the quantity of actual resins is determined by calculation. The results of determining the actual resins are expressed in mg/100 ml of fuel.
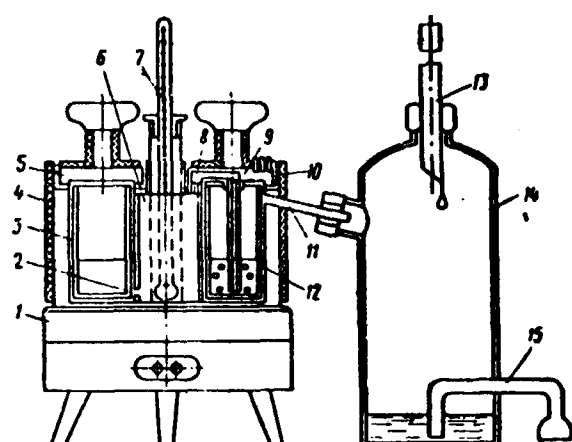
Fig. 12. Diagram of the instrument for determining the actual resins according to GOST 8489-58: 1 — electric heater; 2 — connecting channel; 3 — beaker for water; 4 — housing; 5 — cover; 6 — container for overheating water vapor; 7 — thermometer; 8 — connecting channel; 9 — cover; 10 — water vapor supply tube; 11 — steam-escape tube; 12 — beaker with the fuel being tested; 13 — refrigerator; 14 — condenser; 15 — siphon tube.

The induction period characterizes the tendency of a fuel towards gumming. This characteristic is very important and is determined according to GOST 4039-48 in an instrument, the diagram of which is shown in Fig. 13. A quantity of 100-ml of fuel is poured into a glass bulb and is covered with an hour glass and placed into a special metal bomb. The bomb is filled with oxygen under a pressure of 7 kg/cm^2, is sunk in boiling water and maintained in it until the manometer on the bomb does not show a drop in pressure. This means, that the fuel has begun to oxidize, i.e., resins are forming on the steel in it. The time in minutes, during which the pressure in the bomb remained constant with the fuel temperature at 100°C is called the *induction period*. The greater the induction period, the more stable the fuel in respect to gumming, the longer it can be stored without fearing the formation of resins.

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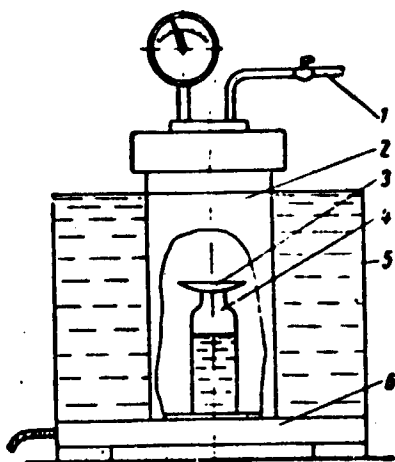
Fig. 13. Diagram of the instrument for determining the induction period: *1* — tube; *2* — metal bomb; *3* — hour glass; *4* — bulb with the fuel to be tested; *5* — vessel with water; *6* — electric heater.

The thermal stability of a fuel characterizes its resistance to the formation of deposits during heating in the presence of air and metals. It has an especially important meaning for fuel for a supersonic aircraft. Under the effect of high temperatures and the catalytic effect of metals deep chemical changes can occur in the fuel with the formation of deposits in the form of liquid and solid substances.

The thermal stability is determined according to GOST 11802-66 with the TSRT-2 instrument (Fig. 14). The essence of the method consists of oxidizing the fuel in the instrument at a temperature of 150°C for 5 h in the presence of electrolytic copper. The oxidized fuel is filtered through a decalcified paper filter and the quantity of deposit formed is determined by weight. Simultaneously the pressure in the bomb, established 1.5 h after the beginning of the experiment is controlled. For T-2 fuel the pressure should be 1.7-2.0 kg/cm^2, for TC-1 — 1.0-1.5 kg/cm^2, etc.

Recently to evaluate the thermal stability of fuels under dynamic conditions special laboratory devices have been developed on which the drop in pressure on the filter is measured. The dependence of the drop in pressures on the filter on the temperature of the fuel being filtered can serve as an index of the stability of fuels at elevated temperatures. For stable fuels the drop in pressures on the filter in practice does not depend on the temperature of the fuel. For slightly stable fuels the drop in pressures

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increases with an increase in the temperature of the fuel. Figure 15 gives the fundamental diagram of the device for determining the thermal stability under dynamic conditions.
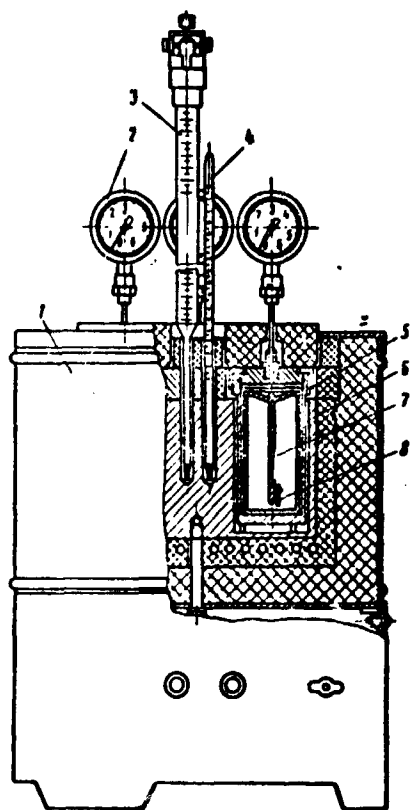
Fig. 14. Diagram of the instrument for determining the thermal stability according to GOST 11802-66: *1* — thermostat; *2* — manometer; *3* — contact thermometer; *4* — mercury thermometer; *5* — steel bomb; *6* — beaker; *7* — glass rod; *8* — metal plate.
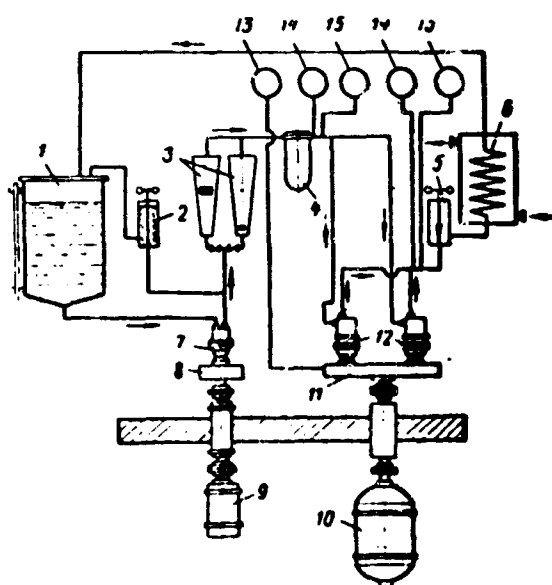
Fig. 15. Line diagram of a device with a fuel pump from a turbojet engine for testing fuel by circulating pumping: *1* — tank for fuel; *2* — bypass valve; *3* — *flow meters; *4* — filter; *5* — throttle valve; *6* — refrigerator; *7* — booster fuel pump; *8* — reduction gear; *9-10* — electric motors; *11* — reduction gear; *12* — high pressure fuel pumps; *13* — tachometer; *14* — manometer; *15* — thermocouple.

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Corrosive properties. The hydrocarbon part of the modern petroleum aviation fuels in practice does not cause the corrosion of. metals and alloys. Corrosive **aggressiveness** is caused mainly by the presence in the fuel of such substances as sulfur, sulfurous compounds, organic acids, water, nitride compounds, and others. Corrosive aggressiveness of a fuel depends on its stability. Slightly stable fuels as a rule, are more corrosive than active. Corrosive properties are evaluated according to the following indicators: by testing on a copper plate, by the quantity of sulfur and sulfurous compounds in the fuel, and by organic acidity.

The test on a copper plate according to GOST 6321-52 is accomplished in the following manner: a plate of pure electrolytic copper of standard sizes is stood in the fuel for three h at 50°C, then its surface is compared with the color of plates not undergoing the test. The appearance on the plate of black, dark brown, or gray steel films and spots indicates the content in the fuel of active sulfurous compounds able to **cause** corrosion. In the absence of a change in the color of the plate the fuel is considered to have passed the test.

The amount of sulfur in a fuel is determined according to a GOST 1771-48 by burning 1.5-5.0 m*l* of test fuel (depending on the sulfur content in the fuel) in the instrument whose diagram is shown in Fig. 16. During combustion the sulfurous anhydride being formed is trapped and the amount of it is determined by the volumetric method. The amount of sulfur in the fuel is judged from the amount of anhydride.

The content of mercaptan sulfur in a fuel is determined according to GOST 6975-57 by titration of the tested fuel with an ammoniacal solution of copper sulphate. Mercaptans interacting with the ammoniacal solution of copper sulphate, form mercaptides of copper. The amount of mercaptan sulfur is strictly limited in fuels because it causes the strong corrosion of metals.

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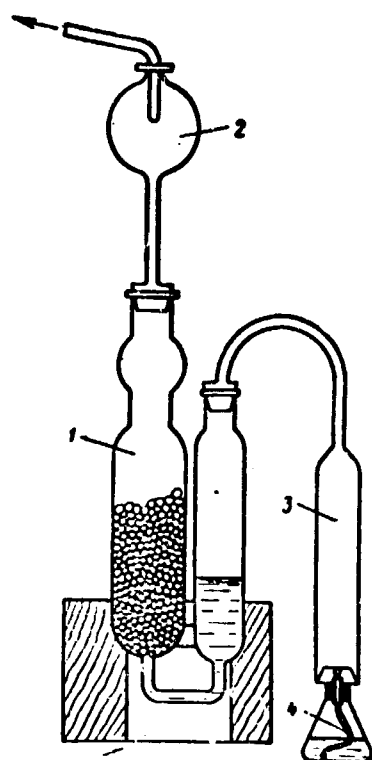
Fig. 16. Diagram of the instrument for determining the amount of sulfur: *1* — adsorber; *2* — spray trap; *3* — lamp glass; *4* — lamp.

Under organic acidity we understand the presence in the fuel of compounds of a acidic character, which are able to cause the corrosion of metals. Napthenic (RCOOH) acids, phenols (C_6H_5OH), asphaltere acids, etc. The acidity of fuels is determined according to GOST 6041-51. The fuel is processed with **ethanol**, which dissolves organic acids, and is titrated back with a solution of caustic potash. The acidity is expressed in mg of KOH necessary to neutralize 100 m*l* of fuel.

The low-temperature properties determine the behavior of fuels with a decrease in temperatures. They are judged according to the cloud temperature and the beginning of crystallization. The cloud temperature is called the temperature at which a fuel begins to grow turbid as a result of the separation out of microscopic water droplets, microcrystals of ice, or hydrocarbons.

The temperature of the beginning of crystallization of a fuel
is called the maximum temperature at which the first crystals visible
to an unaided eye appear in the fuel.

The cloud temperature and the temperature of the beginning of
crystallization are determined according to GOST 5066-56 in the
following manner (Fig. 17): a standard glass test tube 2 with mixer
1 is placed into another test tube 4, which is an air bath, and all
this is placed into vessel 3 with a cooling mixture. Fuel poured
into the test tube with the mixer, is cooled and observe either
for turbidity, or for the appearance of crystals.
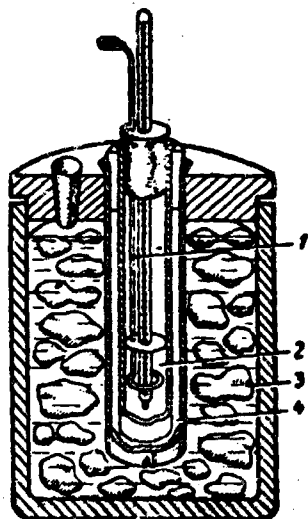
Fig. 17. Diagram of the
instrument for determining
the cloud temperature and
the temperature of
crystallization.

The flammability of fuels is determined according to the flash
temperature and the temperature of spontaneous combustion.

The flash temperature is called the minimum temperature at
which the vapors of fuel, being heated under standard conditions,
form a mixture with the surrounding air, which flares up when a
flame is applied to it. Determination of the flash temperature of
fuels is accomplished in a closed type instrument (Fig. 18) according
to GOST 6356-52. The essence of determination consists of the
following: the instrument is heated by a burner or an electrical

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instrument with a determined rate of increase in the temperature.
At a temperature 10°C lower than the expected flash temperature a
test for flashing is begun at each 1°C for fuels with flash
temperature up to 50°C and at each 2°C — for fuels with a flash
temperature of above 50°C. The flash temperature is taken as the
temperature shown by the thermometer at the appearance of the first
dark-blue flames over the surface of the fuel. It depends upon the
pressure of the fuel vapors: the higher the pressure, the lower the
flash temperature. The flash temperature determined in a closed
instrument, is that temperature at which the pressure of the vapors
of a given fuel reaches 7-10 mm Hg. If, for example, the flash
temperature of a fuel is equal to 35°C, then this means that at
35°C the pressure of the vapors of this fuel reaches approximately
7-10 mm Hg.
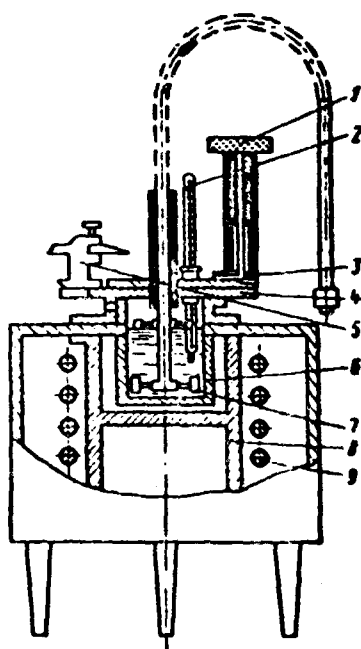
Fig. 18. Diagram of a closed type instrument
for determining the flash temperature: 1 —
handle for controlling the folds; 2 — thermo-
meter; 3 — mechanism for controlling the folds;
4 — cap; 5 — igniting device; 6 — beaker with
the fuel being tested; 7 — mixer; 8,— housing;
9 — electric heater.

The temperature of spontaneous combustion is called the minimum
temperature at which fuel ignites itself without an outside open
source of flame. The temperature of spontaneous combustion is not
a constant value and depends strongly on the method of evaluation

being used. In the state standards the temperature of spontaneous combustion of a fuel is not standardized.

Carbon-deposit forming capacity. During the combustion of fuels a carbon deposit is formed on parts of the combustion chamber — a solid film of from hundredths of a fraction to one millimeter in thickness. The composition of the carbon deposit is very complex and thus far has not been studied in detail. However it is reliably known, that the carbon deposit consists of an organic part — the products of the deep oxidation and condensation of hydrocarbons, sulfur-nitrogen organic compounds, and an inorganic part — particles of the products of wear, dust, and the products of incomplete combustion.

For a long time the carbon-deposit forming capacity of aviation fuels was not evaluated because it was considered, that in piston engines the amount of carbon deposit did not depend on the properties of fuels and in jets — the carbon deposit does not have a harmful effect, because the amount of it is small. These views have recently changed considerably and great importance has begun to be attached to an evaluation of the carbon-forming capacity of fuels.

In connection with the seriousness of the problem of carbon formation in gas-turbine engines investigations are being conducted on the development of methods of evaluating the carbon-deposit forming capacity of fuels under laboratory conditions. Already there are small laboratory instruments and devices which give possibility of evaluating a small quantity of fuel in a short time for its carbon-deposit forming capacity.

Professor Ya. M. Paushkin with his colleagues has developed a laboratory instrument to evaluate th carbon-deposit forming capacity (Fig. 19). When 2-3 g of fuel is burned a carbon deposit is formed on the nozzle part of the combustion chamber and the amount of carbon deposit is determined by weighing the nozzle part.
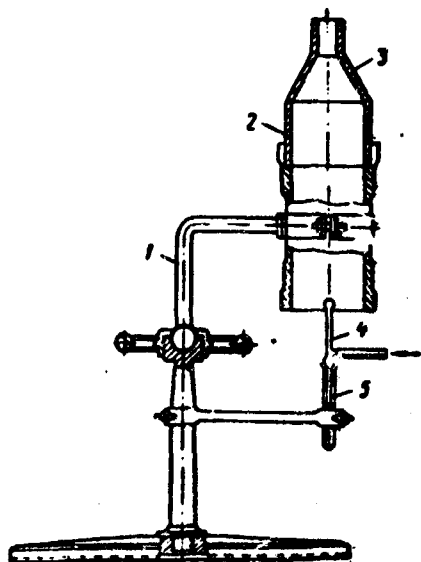
Fig. 19. Diagram of the instrument for determining the carbon-deposit forming capacity of fuel: 1 — support; 2 — combustion chamber; 3 — nozzle; 4 — injector; 5 — vessel with the fuel being tested.

Professor Ya. B. Chertkov with his colleagues has developed an instrument, on which it is possible to evaluate the carbon-deposit · forming capacity of fuels under various conditions of burning, characterized by the coefficient of the excess of air from 0.5 to 4.5. The fuel consumption for one determination — 1-3 ml. Duration of the test — 30 min.

Along with the direct methods determination of the carbon-deposit forming capacity of fuels is also indirect.

Determining the height of sootless flames and the coefficient of smudging and volatility relate to this.

The height of sootless flames is determined according to GOST 4338-48 in a wick lamp (Fig. 20).

Into vessel 4, 10 ml the fuel to be tested are poured. The wick of the lamp is ignited and the height of the sootless flames are measured on scale 1 (the point of smudging according to specifications of the USA and England).
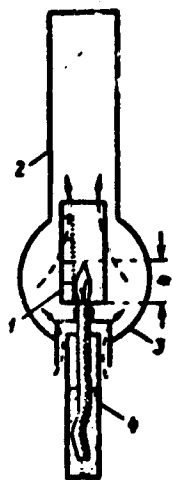
Fig. 20. Diagram of a wick lamp for determining the height of sootless flames:
1 — scale; 2 — lamp glass; 3 — combustion chamber; 4 — vessel with the fuel being tested.

The greater the height of the sootless flames, the lower the carbon-deposit forming capacity. This is confirmed by the following dependence:

Height of the sootless flame (the
point of smudging), mm........... 12 18 21 23 26 30 43

Amount of the carbon deposit, g.. 7.5 4.8 3.2 1.8 1.6 0.5 0.4

For native aviation kerosenes the height of the sootless flame is not permitted to be less than 20-25 mm.

The coefficient of smudging and volatility is calculated as the sum of two terms

$$КДЛ = B + 0.42C_{204.4°c}.$$

where КДЛ — the coefficient of smudging and volatility; B — the point of smudging; $C_{204.4°c}$ — the amount of the fractions boiling away at 204.4°C, % by volume.

The coefficient of smudging and volatility is used in the USA and England to evaluate the carbon-deposit forming capacity of broadly fractional fuels. According to English specifications the size of the coefficient of smudging and volatility should not be below 52.

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Aromatic hydrocarbons possess the greatest tendency towards carbon formation. In the GOST on aviation fuels the aromatic hydrocarbons content is limited: it should not exceed 20% by volume. In foreign specifications a limitation has been introduced into a number of brands on the aromatic hydrocarbons content in them which boil away at a temperature above 204.4°C, - not more than 3% by volume. In native jet fuels according to data from N. A. Ragozin on aromatic hydrocarbons which boil away at a temperature above 204.4°C, there is from 1.2 to 2.6%.

Antiwear properties. Great importance is attached to the evaluation of the antiwear properties of jet fuels because the fuel is simultaneously a lubricating medium for complex, expensive fuel units.

The most acceptable method of evaluating the antiwear properties of fuels is to test them on special laboratory devices which either completely imitate the operation of the fuel system of an aircraft, or which imitate the basic processes, which take place in the operating parts. Imitiation of the fuel system or of its parts causes considerable complication of the laboratory devices, an increase in the test time and in the quantity of fuel for one test.

It is more correct to accomplish the first stage of the tests on the antiwear properties of fuels on relatively simple laboratory devices, which imitate the basic processes of friction and wear. On such devices, it is possible in a short space of time and with a small quantity of fuel to determine the basic antiwear characteristics of a fuel: the dependence of wear on contact pressures, the speed of relative movement of the operating parts, and the temperature of the fuel.

Figures 21 and 22 give the diagram of laboratory devices designed by A. F. Aksenov, A. A. Litvinov, A. I. Terekhin, Yu. G. Nekipelov for evaluating the antiwear properties of fuels during rolling friction and slip friction.
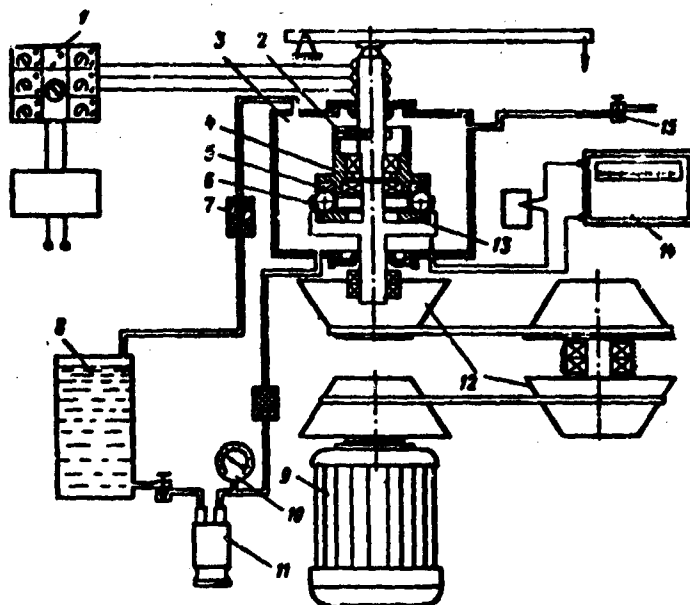
Fig. 21. Line diagram of a device for determining the antiwear
properties of aviation fuels during rolling friction: *1* — amplifier;
2 — sensitive beam; *3* — fuel chamber; *4* — head; *5* — bearing clip;
6 — separator; *7* — filter; *8* — fuel tank; *9* — electric motor; *10* —
manometer; *11* — pump; *12* — pulleys; *13* — specimen; *14* — micro-ammeter;
15 — valve.
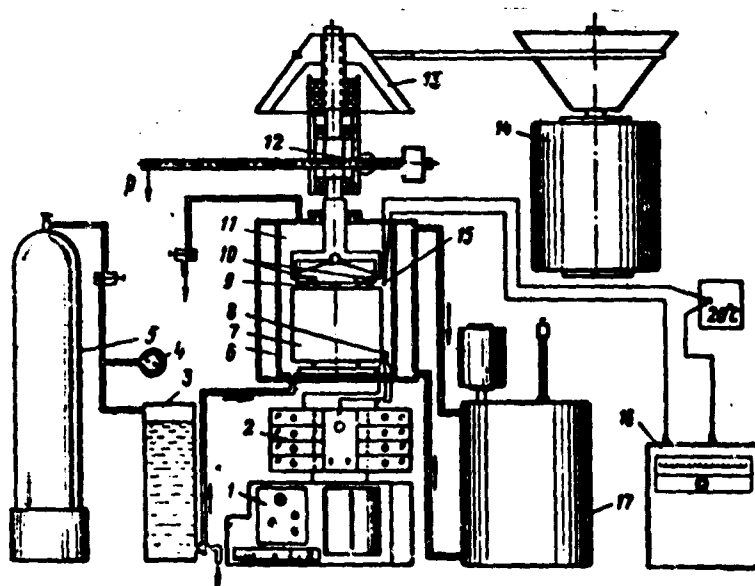
Fig. 22. Line diagram of a device for determining the antiwar
properties of aviation fuels during slip friction: *1* — H-105 oscillo-
graph; *2* — 8ANCh-7M amplifier; *3* — fuel tank; *4* — standard manometer;
5 — tank with nitrogen; *6* — heat carrier chamber; *7* — moveable block;
8 — stress beam; *9* — ball; *10* — specimen; *11* — fuel chamber; *12* —
loading apparatus; *13* — pulley; *14* — electric motor; *15* — thermo-
couple; *16* — micro-ammeter; *17* — TS-16 thermostat.

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The device for evaluating the antiwear properties during rolling friction consists of a friction assembly, an airtight drive chamber, thermostat, loading system, system of circulating the fuel through the chamber, and devices for the measuring the temperature of the fuel. The rolling friction assembly consists of a flat specimen and a separator with balls. Determining the antiwear properties of fuels on this device is accomplished in the following manner: the rolling friction assembly is put together, the chamber is filled up with the fuel to be tested, the necessary temperature regime is created, and the drive for the device is turned on is the required mode of circulation is established, and the given contact pressures are created on the specimens with the aid of the loading system. After testing the amount of wear on the path of friction of a flat sample is measured.

In the process of testing the temperatures of the fuel are recorded. From the results of the tests the dependence of the wear of a specimen on the contact pressures, the temperature of the fuel, and of the rate of rolling is determined.

A device for evaluating the antiwear properties of jet fuels during slip friction has the same fundamental assemblies and systems (see Fig. 22). The friction assembly consists of a flat specimen $d = 60$ mm and three immobile balls $d = 25$ mm, being pressed by a determined axial pressure against the flat specimen. The amount of wear is determined from the change in the diameter of the spot of the wear of the ball specimens or by the amount of wear of the flat specimen.

The theoretical basis of the methods of evaluating the antiwear properties of jet fuels on the described devices is the known fact that for any rubbing pairs there exist such conditions (contact pressures, speeds of relative movement, temperature, lubricating medium, etc.), at which on the friction surfaces there develops and steadily exists a chemical form of wear, characterized by low wear rates, smooth polished friction surfaces, and small coefficient of

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friction. With a change in these conditions the chemical form of wear becomes wear by gripping with a very large rate of wear and complete damage to the surfaces up to jamming.

Therefore, it is necessary to determine under laboratory conditions the limits of existence of chemical wear for a given type of fuel and the rate of chemical wear.

Control indicators. The density, iodine number, ash content, the content of mechanical impurities, water, water-soluble acids and alkalis, and the aniline point relate to these.

The density is called the mass of substances contained in a unit of volume

$$\rho = \frac{m}{V} ;$$

In practice the size of the relative density equal to the ratio of the density of the fuel at the temperature of measurement to the density of water at a temperature of 4°C and standard atmospheric pressure is often used:

$$d_4^{t} = \frac{\rho_m^{t}}{\rho_b^{4°C}} ;$$

Since the density of water at 4°C is equal to 1 g/cm^3, then the relative density of the fuel is numerically equal to its density. In literature the relative density of fuel is frequently called simply the density and is designated d_4^{t} (t — temperature at which the density has been determined).

With a decrease in the temperature the density increases, and with an increase — it decreases. Therefore, in order to obtain comparable values, it has been accepted that density measured at any temperature, be applied to the density at 20°C using the following formula:

$$d_4^{20} = d_4^{t} + \gamma (t - 20),$$

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where d_4^{20} — the density of fuel at 20°C; d_4^t — the density of fuel measured at a given temperature; γ — a temperature correction for density; t — the temperature of the fuel at the moment the density is determined.

The mean temperature correction of density can be determined according to the formula

$$\gamma = (18,310 - 13,233 d_4^{20}) \, 10^{-4}.$$

The density of fuel also depends on the pressure: with an increase in pressure in increases. Thus, with an increase in the pressure to 100 kg/cm^2 the density increases on the average by 2-3%. The density is measured according to GOST 900-47 by an areometer, hydrostatic weights, and by a pycnometer. The simplest method of measuring the density is with the aid of an areometer.

The iodine number — the amount of iodine, expressed in grams, joined to 100 g of fuel. During the treatment of fuel with iodine it joins to unsaturated hydrocarbons, therefore the presence in a fuel of slightly stable unsaturated hydrocarbons is judged according to the iodine number. For example:

$$CH_2 = CH_2 + I_2 \rightarrow CH_2I - CH_2I.$$
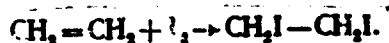
The iodine number is determined according to GOST 2070-55 or GOST 8997-59.

The *ash content* of fuel is determined according to GOST 1461-52 in the following manner: 25 g of fuel are evaporated in a crucible and a residue is roasted to complete calcination. The ashes obtained are expressed in percentages to the given fuel mass. The ash content is an indirect characteristic tendency of fuels to carbon-deposit formation.

Mechanical impurities in fuel are very dangerous because they lead to the rapid wear of parts of the fuel apparatus and to clogging of the filters. They are determined by the weight method according to GOST 6370-59: 100 g of fuel is filtered through ash-free filters, is dried and weighed. The mechanical impurities obtained are expressed in percentages to the given fuel mass. A content of mechanical impurities in the fuel of less than 0.005% is accepted as an absence of them.

However the experience in the operation of aviation fuel apparatus testifies to the fact that mechnical impurities are contained in fuel even to the extent of less than 0.005%, can substantially increase the wear of the parts of a fuel system. Therefore today more precise laboratory methods have been developed for determining the mechanical impurities content, which makes it possible to limit their content in fuels to 0.001%.

The water content. All fuels in one way or another are hygroscopic. The hygroscopic water content in aviation fuel is determined according to GOST 8287-57. The method is based on the interaction of calcium hydride with the water contained in the fuel, and measuring the volume of hydrogen given off in this case:

$$CaH_2 + 2H_2O = Ca(OH_2) + 2H_2O.$$

For the quantitative determination of water in the fuel a special instrument is used (Fig. 23). The fuel being tested in the amount of 100 ml is poured into bulb *3*. Petcock barrel *4* with calcium hydride is put carefully into the joint of the bulb so that the opening filled with calcium hydride is located on top. With the aid of electric motor *1* magnetic mixer *2* is set into action during which the continuous rotation causes the saturation with fuel vapors of bulb *3*, Drexel *5*, and gas buret *9* with open valve *6* and closed valve *7*. Petcock barrel *4* is turned 180° at the joint and in this case the calcium hydride is poured out into the fuel.
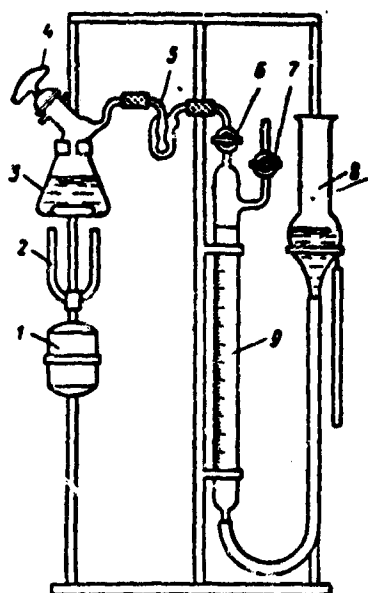
Fig. 23. Diagram of the instrument for quantitative determining the amount of hygroscopic water.

The hydrogen liberated from the fuel is gathered in the buret, gradually sinking equalizing flash *8*. Readings of the volume of liberated hydrogen are accomplished after each 5 min until two subsequent readings will be distinguished by not more than 0.1 mm. The last reading is taken as the calculation. The content of water in the fuel in weight percentages is determined by the calculation method according to the volume of liberated hydrogen.

Water-soluble acids and alkalis. Mineral acids and alkalis are not allowed in fuel because they cause very strong corrosion of the metals of a fuel apparatus. The presence of water-souble acids and alkalis is established according to GOST 6307-60 by the reaction on litmus of water extraction.

The aniline point — the temperature at which fuel and aniline $C_6H_5NH_2$ mix together in any ratios. Determination of aniline points is based on the unequal solubility of various hydrocarbons in polar solvents. The critical temperature for dissolving the fraction of paraffin hydrocarbons, which boil at a temperature of 95-122°C in aniline — 70.3°C, of napthenes — 40.3°C, and of aromatic hydrocarbons — 15°C.

There exist two methods of determining the aniline points: equal volumes and maximum aniline points.

In the first case equal volumes of aniline and of hydrocarbons are taken and the temperature of their complete mixing is determined. The maximum aniline point is determined by increasing the quantities of aniline and fixing the maximum temperature, above which complete mixing of both phases in all ratios takes place.

The method of aniline points is used for the quantitative determination of aromatic hydrocarbons. For this we use the aniline coefficients, obtained on the basis of experimental materials and showing which percentage of the aromatic hydrocarbons in the fuel causes a decrease in the aniline point of 1°C. With an increase in the content of aromatic hydrocarbons in the fuel the aniline point decreases.

C H A P T E R   III

ENGINEERING BASES OF THE USE OF AVIATION FUELS

1. The Stability of Fuels During Transportation and Storage

From the moment of production of fuels up to their use in aircraft is, as a rule, a prolonged time. This is associated primarily with the fact that there should be a determined reserve of fuels in aircrafts for uninterrupted work. Furthermore, time is necessary to transport and filter the fuel and for other operations. The length of time, during which the fuel can be used on directly is regulated by special documents. The limitation on the periods of storage for fuels, and also the strict rules for the transport and conditions of storage are caused by the fact that all petroleum fuels to one degree or another change their initial composition, and therefore, their properties.

The hydrocarbons in the composition of a fuel during prolonged storage under the influence of oxygen in the air, metals, light, heat, and other factors can be oxidized with the formation of resinous substances, and liquid and solid deposits. They can be formed in such a quantity that the use of the fuel will become impossible.

In transporting and storing fuel the factors which most strongly influence its oxidation and gumming are: temperature, the amount of the surface in contact with the air, the presence of metals, and the concentration of water in the fuel.

With an increase in the temperature the processes of oxidation and gumming are accelerated. Because of this in the summer period, especially in the southern regions, when storing fuels in over ground tanks the formation of resinous substances goes faster, than when they are stored in underground tanks. Thus, for instance, when storing fuel for five months at a temperature of 15-20°C 9 mg of resins per 100 ml of fuel were formed, but at a temperature of 35-38°C - 53 mg, i.e., 6 times more.

The greater the surface of fuel in contact with the air and the greater the volume of air space over the fuel, the faster the fuel becomes resinous. Figure 24 shows the dependence of the actual resins content on the duration of storage of the fuel under the various filling conditions of a vessel. Other conditions being equal, in a vessel filled 50%, after five months 3-3.5 times more resinous substances are accumulated in the fuel than in a vessel completely filled. A number of metals with which the fuel comes in contact during transport and storage are catalysts, which accelerate oxidation and gumming. The strongest catalysts are nonferrous metals: lead, zinc, aluminum, copper (Table 5).
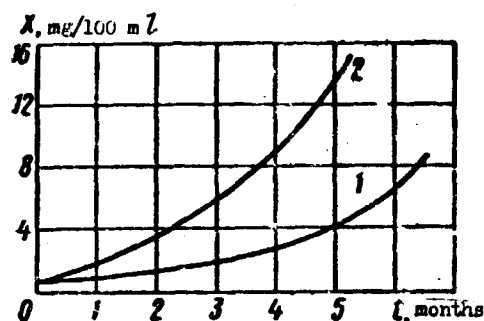
Fig. 24. The formation of actual resins (X) during storage: 1 - in tanks, filled to capacity; 2 - in tanks filled to 50%.

The water found in fuel during transport and storage accelerates the processes of oxidation and gumming.

The most correct scientific explanation of the processes of auto-oxidation of hydrocarbons can be given on the strength of the theory of chain reactions. By chain reactions we usually mean those

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reactions, as a result of which along with the final products there always is formed an activated basic substance or an unstable intermediate compound. Briefly stated, in the reaction mass there appear substances (radicals), accumulating in themselves the energy of the reation, and to continue the reaction chain it is partically not necessary to feed energy from the outside.

Table 5. Effect of metals on the gumming of fuel (before storage the fuel contained 5 mg of resins per 100 ml of fuel).

Metal	Content of actual resins, mg/100 ml	
	storage 1 month	storage 2 months
Iron............	25	33
Aluminum........	28	40
Zinc............	31	46
Lead............	48	162

The most extensive studies of chain reactions, and especially of the processes of auto-oxidation, belong to Academician N. N. Semenov and his students.

According to the chain theory the processes of auto-oxidation begin with the reaction of the onset of the oxidation chain. In this case it is most probable that the appearance of the primary radicals can occur because of the interaction of molecules of hydrocarbon with oxygen

$$RH + O_2 \rightarrow R' + HOO'.$$
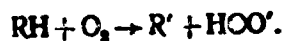
The development of the reaction chain of auto-oxidation is presented in the following manner:

$$R' + O_2 \rightarrow RO_2'; \quad RO_2 + RH \rightarrow R' + ROOH , \text{ etc.}$$

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In this way the primary product of the reaction is hydro-peroxide.

However this very simple diagram does not explain the low rate of the auto-oxidation reactions of hydrocarbons, their autocatalytic character and some other factors. N. N. Semenov assumed the presence of the so called "chains of degenerated branding," the essence of which is that as a result of the primary reaction an intermediate relatively stable compound is formed which subsequently independently from the basic reaction can decompose, giving a beginning to new chain reactions. In the process of auto-oxidation such an intermediate compound is hydrogen peroxide. The decomposition and further trans-formation of hydrogen peroxide can go according to the pattern.

$$ROOH \rightarrow RO' + OH; \quad RO' + RH \rightarrow R' + ROH;$$
$$OH + RH \rightarrow R + H_2O \text{ , etc.}$$
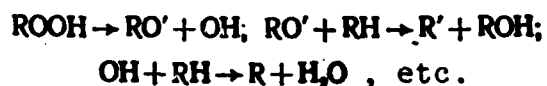
Inasmuch as every molecule of hydrogen peroxide gives a begin-ning to several new chains, the rate of the reaction increases sharply.

The reactions terminating the chain of auto-oxidation can be accomplished both by recombining two radicals, for example $R' + R' \rightarrow R - R$, and by transforming hydrogen peroxide into inactive stable end products - alcohols, aldehydes, ketones, etc. With the accumula-tion of the end products of oxidation the reaction speed drops.

In a molecule of hydrocarbon the bond C—C is weaker than the bond C—H, however in most cases the attack of oxygen is directed to the bond C—H. N. N. Semenov explains this by the fact that in a molecule of hydrocarbon the bond C—C is protected by atoms of hydrogen and in order to move them apart, an investment of additional energy is necessary (on the order of 10-15 kcal). In that case rupture of the bond C—H becomes energetically more probable.

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From the energy point of view, auto-oxidation should flow primarily on the tertiary C—H bond as the weakest. The primary C—H bond on the contrary is sufficiently durable and must be subjected to oxidation to the smallest degree.

Paraffin hydrocarbons are relatively inert to ordinary chemical reagents, also including molecular oxygen. During auto-oxidation of n-paraffins the second carbon atom from the end of the chain undergoes oxidation. In the presence in the basic circuit of branching oxidation is directed to the tertiary carbon atom. During the oxidation of n-paraffins primary monohydroperoxides are formed. With subsequent oxidation the monohydroperoxides form dihydroperoxide.

Upon decomposition of the monohydroperoxides alcohols, aldehydes, and ketones are formed. Upon further oxidation of them, finer "splinters" or molecules are obtained. The basic products of the decomposition of hydroperoxides are hydroxy acids.

The aldehydes, ketones, and hydroxy acids formed can enter the polycondensation reaction with the formation of solid deposits.

In jet fuel, if we look at it under a microscope, it is possible to detect numerous solid particles. In one cubic millimeter of fuel there are several thousands of such particles, moreover, the smaller the size of the particles, the larger their quantity. It has been reliably established, that in transporting and storing fuel both where air is accessable, and in airproof reservoirs the quantity of micro-impurities increases. The rise in the quantity of microimpurities takes place not only because of external pollution, but also due to the processes taking place in the fuel. Fine particles (up to 5 μm) can be found in a suspended state for a very prolonged time, but particles more than 5 μm in size gradually becomes a sediment or settle on the walls of the reservoir. Thus, during storage the processes of accumulation and precipitation in the form of solid phase microimpurities continuously take place in the fuel.

The microimpurities in fuel consist of three constant components: organic and mineral compounds and water. The composition of microimpurities consists of: carbon, hydrogen, sulfur, nitrogen, oxygen, and ash elements (iron, silicon, and others).

The relatively large quantity of oxygen in the composition of microimpurities testifies to the fact that their accumulation in fuel and the liberation in the form of a solid phase is associated with the processes of oxidation. In fresh, uncontaminated, jet fuel the quantity of microimpurities constitutes 0.5-1.5 g/t. After prolonged storage in iron reservoirs this quantity can reach 3-5 g/t, and under especially unfavorable conditions (during intensive mixing in contact with water) - 10-20 g/t. Therefore, after storage fuels must be thoroughly filtered.

2. Filtration of Fuels

The fuels put into aircraft, should not contain mechanical impurities and water or should contain them in such quantities, that do not have an effect on the operation of the fuel system. Today there exists a multistage system of filtration for fuels, which provides for the removal of mechanical impurities and water at various stages of transportation, storage, and loading into aircraft. As an example let us examine the following multistage filtration system for aviation fuel.

The first stage - the filtration of fuels as they are being drained from the method of transportation into the reservoirs at an airport. Filtration is accomplished with a purification fineness of approximately 20-25 μm. The second stage - filtration upon delivery of the fuel from the reservoir to a fuel tank or to a system of centralized servicing. In this stage filtration is provided with a purification fineness of approximately 5-10 μm. The third stage - filtration of the fuel by the filters on a fuel tank and at stationary points of the centralized servicing during servicing of aircraft with purification fineness of approximately 5-7 μm. The fourth stage -

filtration of the fuel by the fuel filters of the aircraft with a purification fineness of approximately 5-10 μm.

The need for multistage filtration is explained by the fact that the microimpurities in fuels appear both as a result of contamination of the fuel from the outside (by atmospheric dust, by the products of corrosion of the fuel pipes and reservoirs, etc.), and as a result of the continuous oxidation of fuel in the process of storage. Thus, if the fuel was thoroughly purified of contaminants when it was drained into reservoirs, then after a determined period of storage microimpurities again accumulates in the fuel and the need for filtration appear again.

The filtration of fuels is accomplished with special filters of fine purification with a large permeability. To sepearate the water suspended in the fuel special filter-separators are used.

The characteristics of fine purification filters for fuels in civil aviation airports are given in Table 6.

Table 6. Characteristic of filters for purifying fuels.

Characteristic	Filter		
	TF-2M	FGT-30/60	ST-500-2
Nominal permeability, l /min..........	500	500	500
Drop in pressure on the filter, kg/cm^2..............................	0.3-1.5	0.3-2	1.5
Completeness of purification..........	0.9	0.75	0.85
Fineness of purification, . m..........	20-25	30-35	20-30

3. Pumpability of Fuels

The fuel supplied to the fuel tanks of an aircraft must while the power plant is operating be continuously supplied to the combustion chamber in strict correspondence with the given law of fuel feed. The continuity of the fuel supply should be provided for in all conditions of operation of an aircraft (temperature, altitude, moisture, etc.).

The supply of fuel with all other conditions being equal can be disrupted, if its viscosity becomes greater than the calculated or if a new phase (solid or gaseous) begins to be intensively liberated in the fuel. With an increase in the viscosity of the fuel (at low temperatures) the losses of pressure increase in the pipelines because

$$\Delta P_{\text{труб}} = \lambda \frac{L}{d_э} \rho \frac{v^2}{2g}.$$

where L - the length of the pipeline; $d_э$ - the equivalent diameter (the ratio of the quadruple area of the given cross section to the perimeter of the cross section); ρ - the fuel density, kg/m^3; v - the rate of pumping, m/s; g - the acceleration of earth attraction, m/s^2; λ - the coefficient of losses due to friction.

For a laminar flow and circular pipelines

$$\lambda = \frac{64v}{d_э v}.$$

where v - the kinematic viscosity, m^2/s.

Therefore, there exists such a critical value of the viscosity v, at which the losses in pressure in the pipelines increase so much that the supply of fuel can cease.

If the conditions are created, at which a new phase begins to be formed in the fuel especially solid or gaseous, the supply of fuel can be disrupted due to clogging of the filters or to the appearance of cavitation conditions of operation of the pumps. The intensive formation of the solid phase in fuel is observed at negative temperatures, and the formation of the gaseous phase - during high-altitude flights. In accordance with these conditions let us examine the pumpability of fuels at low temperatures and in high-altitude flights.

The pumpability of fuels at low temperatures. Modern transport aircraft of civil aviation can be used at temperatures of minus 50-60°C. The pumpability of fuels at low temperatures can be

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disrupted as a result of the crystallization or the thickening of hydrocarbons, crystallization of water which is separated from the fuel, and also as a result of an excessive increase in the viscosity of the fuel. Aviation fuels produced by native industry, must have a temperature of the beginning of crystallization not higher than -60°C. The temperature of crystallization of hydrocarbons depends on their chemical structure and molecular weight.

As numerous investigations showed, almost all hydrocarbons that boil away before 200°C, have a temperature of the beginning of crystallization of below -60°C and can be used as a base to obtain aviation kerosense. Of the hydrocarbons which boil away at a temperature above 200°C, it is recommended that monocyclic aromatic and cyclane, and also paraffin (alkanes) of an isomeric structure be used. These hydrocarbons also have a temperature of the beginning of crystallization below -60°C. Paraffin hydrocarbons of a normal structure, polycyclic, aromatic, and naphthenic hydrocarbons which boil away at temperatures above 200°C, can be crystallized at temperatures above -60°C. These hydrocarbons can be used as components in aviation fuels only in those quantities that will not lead to an increase in the temperature of crystallization of the fuel above -60°C.

The pumpability at low temperatures can be disrupted as a result of the freezing of the water, which is found in the fuel in a dissolved state (hygroscopic water), in the form of emulsions, or in a free state.

All hydrocarbons are able to dissolve a determined amount of water. The solubility of water (hygroscopicity) depends on a chemical structure and the molecular weight of the hydrocarbons, and also on external factors: the temperature of the fuel, moisture of air over the fuel atmospheric pressure.

Water is dissolved in the greatest quantity in aromatic hydrocarbons. Close to them in dissolving capacity are the unsaturated hydrocarbons. Paraffin hydrocarbons dissolve in the least quantity of water (Table 7).

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Table 7. Effect of the chemical structure of a hydrocarbon on its hygroscopicity.

Hydrocarbon	Solubility of water, % by weight, at a temperature	
	10°C	20°C
Isooctane.........	0.0037	0.0055
Cyclohexane.......	0.0049	0.0087
Benzene...........	0.0400	0.0570

With an increase in the molecular weight of the hydrocarbons their hygroscopicity decreases. With an increase in the temperature the solubility of water in hydrocarbons increases (Fig. 25).
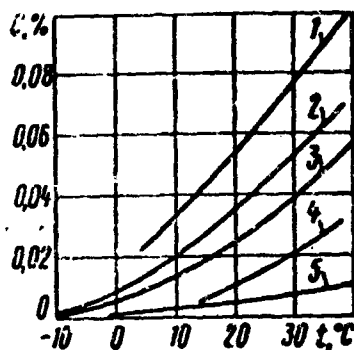
Fig. 25. Dependence of the solubility of water in hydrocarbons on the temperature: 1 - benzene; 2 - toluene; 3 - xylene; 4 - cyclohexane; 5 - isooctane.

As a result of the different chemical composition and different molecualr weight kerosenes and gasolines possess different hygroscopicity which is evident from Fig. 26, where the solubility of water in various fuels has been given according to the data of N. A. Rogozin.
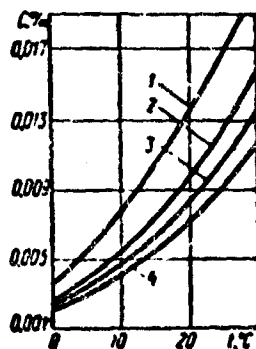
Fig. 26. Solubility of water in various types of aviation fuels: 1 - gasoline; 2 - wide fraction type fuel; 3 - lightened kerosene; 4 - kerosene.

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The works carried out by N. A. Rogozin showed that there are two forms of hygroscopicity in liquids: irreversible and reversible.

The hygroscopicity of a liquid is called irreversible if the water absorbed by the liquid with a change in temperature and moisture is not liberated in the form of an independent liquid phase. Ethanol for example, possesses, such hygroscopocity which is proportion to the absorption of moisture is diluted, and its concentration decreases. Alcohol accumulate absorbable moisture, bonds it and does not liberate it with the sharpest changes in the temperature and moisture in the air.

If a liquid not only absorbs and dissolves moisture in itself but with a change in temperature and moisture in the air it liberates the earlier dissolved moisture from itself in the form of an independent liquid phase, when the hygroscopicity of such a liquid is called reversible. Petroleum fuels possess such hygroscopicity. The accumulation in jet fuels of free water, the formation in them of ice crystals, and also a hoarfrost on the walls of the tanks during storage is caused by the reversible hygroscopicity of the fuels.

The reversible and irreversible hygroscopicity of liquids is explained by the forms of the interaction of molecules of water with the molecules of a liquid. In liquids which possess irreversible hygroscopicity, the molecules of water enter a chemical bond with the molecules of the liquid. In liquids which possess a reversible hygroscopicity, the molecules of water occupy the intermolecular space in the liquid and do not react chemically with it.

The solutions of water in hydrocarbons and fuels in view of the low solubility of water are very diluted. Because of this they comply to Henry's law

$$C = kp.$$

where C - the concentration of water in the hydrocarbon or fuel, g/l; p - the partial pressure of water vapors, mm Hg; k - the coefficient

of proportionality, $g/(l \cdot mm \cdot Hg)$.

Studies showed that the coefficient of proportionality

$$k = \frac{C_{max}}{p_{\text{в}}^{\text{нас}}},$$

where C_{max} - the maximum possible concentration of water in a hydro-carbon or fuel, g/l; $p_{\text{в}}^{\text{нас}}$ - the pressure of the saturated water vapors, mm Hg.

Then

$$C = C_{max} \frac{p^1}{p_{\text{в}}^{\text{нас}}} = C_{max} \, \varphi,$$

where φ - the relative humidity of the air.

Therefore, the concentration of water in a hydrocarbon or fuel at a constant temperature is directly proportional to the relative humidity of the air. The given dependence for some temperatures is shown in Fig. 27.
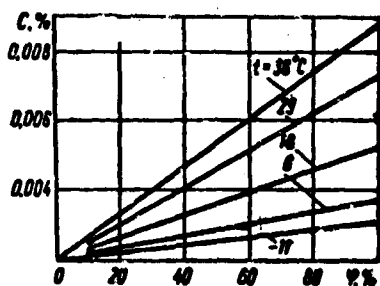
Fig. 27. Dependence of the solubility of water in kerosene on the relative humidity of the air.

Since the relative humidity of the air is not constant, then the water content, dissolved in the fuel is also not constant. With an increase in the relative humidity of the air the fuel is saturated with water and air and the dissolved water content increases. With a decrease in the relative humidity of the air the water content in the fuel decreases.

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The water content dissolved in fuel also decreases with a decrease in the atmospheric pressure (upon lift-off of an aircraft). This dependence, as seen from Fig. 28, has a rectilinear character independent of the relative humidity of the air.
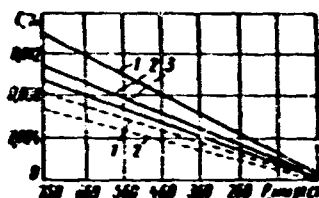
Fig. 28. Dependence of the solubility of water in aviation fuels on the atmospheric pressure: 1 - gasoline; 2 - lightened kerosene; 3 - kerosene; ————ϕ = 75%; --------ϕ = 100%.

With a decrease in the temperature, humidity, or pressure, the liberation of hygroscopic moisture from the fuel occurs in two ways: in the form of finely dispersed droplets of water and by means of vaporization.

If with a constant humidity in the air the temperature changes sharply, then due to the change in the solubility of water in the fuels, the excess moisture falls out in the form of finely dispersed droplets, which in the beginning are found in a suspended state, and then settle on the bottom of the vessel or during negative temperatures form minature crystals of ice. At a constant temperature or with an insignificant change in it when the relative humidity of the air is below 100%, vaporization of the hygroscopic moisture from the fuel takes place. Moisture from the fuel will vaporize until there is achieved a certain equilibrium between the concentration of moisture in the fuel and the concentration of water vapors in the air.

The condensation of moisture from the air as a result of the change in temperature can occur not only on the metal walls of fuel tanks, but also on the surface of cooled fuel. Moreover moisture condensing on the surface of fuel does not freeze immediately, but at first is dissolved or it is spread about in the fuel in the form of a suspension.

The formation and growth of ice crystals in watered down fuels are possible only in a supercooled or supersaturated, with respect to

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the substance being crystallized (water), medium. The degree of supersaturation or supercooling of a medium is wholly determined by the temperature and the chemical composition of the medium.

Water liberated from fuel, which has a temperature below 0°C, in the form of miniature droplets, rapidly freezes throughout the whole volume of fuel, forming fine crystals of ice, which, as a result of their small sizes and density, are retained in a suspended state and over a prolonged time they do not settle to the bottom. However the liberation of microdroplets of water at negative temperatures is not always accompanied by the formation of microcrystals of ice. This is explained by the capability of a droplet of water to be supercooled, in addition the degree of supercooling rises with a decrease in the size of the water droplet. The state of supercooling is unstable, and therefore upon mixing and pumping of the fuel containing supercooled droplets of water, crystals of ice are formed instantly.

The supercooling of fuel leads to cases, which were observed during the winter operation of aircraft, when the fuel in a refueling unit did not contain crystals of ice, but after it was pumped and serviced into the tanks of an aircraft crystals of ice were noticed in the fuel.

The centers of crystallization of the liberated water can be crystals of hydrocarbons and particle of mechanical impurities. The water liberated from fuel with a change in the temperature, humidity, or atmospheric pressure is found in the form of a water and fuel emulsion. A water and fuel emulsion can also be formed when the rules of transport, storage, and pumping are violated, and when free water falls into the fuel. The emulsion of water with fuel is very difficult to detect and to remove from the fuel and therefore it represents a large danger for the normal operation of the systems and aggregates of an aircraft. An emulsion is, as is known, the mixture of two liquids, where one liquid is distributed throughout another in the form of miniature droplets. The sizes of the water droplets in water-fuel emulsions are found within the limits 10-40 µm.

The main danger of emulsified water is that it can cause freezing over of the filters and can disrupt the operation of the fuel system of an aircraft. Droplets of water 10-40 μm in size can for hours be in a suspended state, and in a medium of cold fuel can cool very rapidly, taking the temperature of the fuel, and in this case are susceptible to considerable supercooling.

By numerous investigations by native and foreign scientists have established the following regularity; the smaller the diameter of the water droplets in the emulsion, the lower the temperature to which they can be supercooled. Droplets size 10 μm in size can be supercooled to -41°C, droplets 50 μm - to -36°C, droplets 100 μm - to -30°C, etc.

When a stream of fuel, containing supercooled droplets of emulsified water meets crude and fine purification filters there is a collision of the supercooled droplets of emulsified water with the hard cold surface of the filter. As a result the supercooled water droplets instantly turn into ice, causing a freeze-over of the filter nets.

With considerable watering down of fuels the sizes of the droplets of water can be considerably larger than 40-50 μm. Water settles to the bottom of a vessel relatively quickly and is located in a separate layer. This is the so called free water in fuels. It is easily noticed visually and is relatively easily removed.

The presence of crystals of ice in a fuel can also be as a result of the shedding, sliding down, and the washing of hoarfrost from the walls of vessels and from aircraft full tanks.

To avert the formation of ice crystals in fuel and the freeze-over of fuel filters various methods exist both constructive, and physicochemical.

The following belong to the constructive method: preheating the fuel or the filter, injection of a special liquid onto the filter at the moment of choking of the latter by ice crystals, washing the filter with fuel supplied under pressure from a special pump (hydro-wash), and others.

The physicochemical methods of the averting the formation of ice crystals in fuel and the freeze-over of fuel filters are based on removing the reverse hygroscopicity of petroleum fuels and translating them into irreversible hygroscopicity. In practice this is achieved by introducing various additives into the fuel, which dissolve in the fuel and which possess a high irreversible hygro-scopicity. Such additives can be some alcohols, ethers, and other compounds. The most effective of them was ethylcellosolve - the monoethyl ester of ethylene glycol, proposed by B. A. Englin.

Ethylcellosolve added to the fuel, mixing with the droplets of emulsified water found in the fuel, forms antifreeze (water + + ethylcellosolve) with a low freezing temperature. Thus, when ehtylcellosolve is added to fuel an emulsion of water, will not be found, but an emulsion of low freezing antifreeze. In this way the danger of the formation of supercooled droplets and crystals of water is averted, and consequently, the danger of clogging and freezing over of aircraft fuel filters.

As already indicated, the hygroscopicity of fuel depends on the temperature: the higher the temperature of the fuel, the more it can absorb. One of the methods of combatting crystal formation is based on this feature - the freezing out of water from water saturated fuel.

Freezing out water from fuel is accomplished by storing it in ground vessels for not less than three days at a temperature below -10°.

The lower the temperature of the fuel, the more hygroscopic

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water is liberated from it. After freezing out the water the fuel must absolutely be filtered through the fine purification filter of the refueling unit to remove the crystals of ice from it.

Freezing out is the least effective method of combatting crystal formation in fuels in comparison with the addition of ehtylcellosolve. Even prolonged freezing out at low temperatures does not completely remove the formation of ice crystals. It only decreases the amount of water dissolved in the fuel and thereby decreases the potential possibility of ice crystal formation in the fuel poured into the tanks of an aircraft.

With a decrease in the temperature of the fuel its viscosity and density increases. The change in viscosity depending on the change in the temperature of the fuels is shown in Fig. 29. The viscosity of the fuels exerts a large effect on the pumpability of fuel and in particular on the quality of its dispersion.
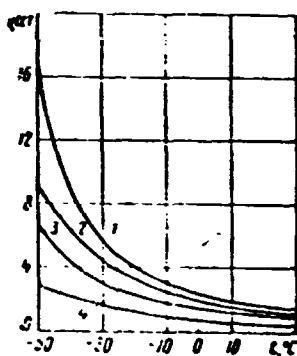
Fig. 29. Dependence of the viscosity of aviation fuels on the temperature: 1 - kerosene; 2 - lightened kerosene; 3 - wide fraction type fuel; 4 - gasoline.

With a considerable increase in the viscosity of the fuel the pumpability and quality of its dispersion is worsened because the rate of discharge of the fuel from the force pumps decreases, the size of the droplets increases, and the angle of dispersion decreases.

The viscosity of jet fuels at a temperature of minus 65-70°C increases so much, that they lose mobility and are very difficult to blend and to pump.

According to existing standards for jet fuels, the temperature at which the fuel loses mobility (the temperature of thickening) is not standardized, but in practice it can be considered that this temperature is 5-10° below the temperature of the beginning of crystallization.

Excessively viscous fuel exerts a large resistance when being pumped through the fuel system which can cause a break in the fuel flow and as a result of this, stoppages in supplying it to the fuel pump.

The pumpability of fuels during high-altitude flights. With an increase in the flight altitude of an aircraft and therefore, with a decrease in the atmospheric pressure the volatility of the fuel increases and dissolved air and other gases are liberated from the fuel. Under these conditions it will not be a homogeneous liquid being pumped through the fuel system, but a mixture consisting of a liquid and gas-vapor bubbles. With an increase in the flight altitude the volume of the gas-vapor phase increases and can reach such a size that the normal operation of the fuel pumps is disrupted. The capacity of the pump sharply decreases as a result of the emergence of a cavitation condition of operation, and in this case the pumpability of the fuel through the fuel system is disrupted. Caviation (Latin cavitas - a hollow, cavity) - this is a formation of gas-vapor bubbles in a moving liquid.

Other conditions being equal the intensity of cavitation increases when using fuels with a large pressure of saturated vapor. The greatest cavitation appears, if the fuel is boiling, i.e., when the pressure of the saturated vapors of the fuel is equal to the external pressure. Thus, the greater the pressure of the saturated vapors of the fuel, the lesser the height at which this fuel will begin to boil and at which the greatest cavitation will be observed. Thus, for instance, the fuel with vapor pressure equal to 360 mm Hg at 20°C, will begin to boil at an altitude of 9.5 km, and fuel with vapor pressure equal to 40 mm Hg at 20°C, will begin to boil at an altitude of 20.5 km.

In pumping fuel through the fuel system in its separate sections the pressure the fuel is under can be even less than the external atmospheric pressure. Therefore, to determine the height of a fuel system necessary to compare the pressure of the saturated vapors of fuel not with the atmospheric pressure, but with least pressure the fuel is under in the fuel system. Such a pressure is the pressure at the fuel pump inlet (p_{BC}). If the pressure of the saturated vapors of fuel (p_{HAC}) is less than the pressure at the pump inlet, then there is a noticeable cavitation and the pump operates normally. If the pressure of the saturated vapors of fuel is equal to or more than the pressure at the pump inlet, then cavitation appears, the pumping capacity drops sharply, the circulation of fuel is disrupted.

Therefore

$$p_{вc} \geqslant p_{нac} + \Delta p_{кав}$$

where p_{BC} - the pressure of suction, mm Hg; p_{HAC} - the pressure of the saturated vapors of fuel, mm Hg; $\Delta p_{каB}$ - the size of the cavitation reserve, mm Hg.

Thus, in high-altitude flights the pumpability of fuel will be determined by the pressure of its saturated vapors.

To decrease the formation of vapor lock in high-altitude flights it is possible either to use heavier fuels by factional composition, or some operational or structural measure. Thus, for instance, the determined results gives the cooling of the fuel before flight. This method is rather simple and besides decreasing the pressure of the saturated vapors of the fuel, it makes it possible to increase the weight of the fuel supplied to the fuel tanks (due to the increase in the density of the fuel).

With the rise to altitude along with fuel evaporation the process of the liberation of the air dissolved in the fuel takes place which considerably accelerates the formation of vapor-air locks, and therefore, cavitational conditions of operation of the pumps.

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Gasolines dissolve approximately 20-25% air by volume kerosenes
- 13-15% by volume.

The solubility of air in paraffin hydrocarbons is higher, than
in aromatic hydrocarbons.

The solubility of air in fuels changes considerably from the
external pressure. In proportion to the decrease in exteral pressure
the solubility of air in fuels falls. Because of this during the
rise of an aircraft to altitude the air dissolved in the fuel begins
to separate from it. The liberated air leaves the tanks of the air-
craft through the vent system also bringing fuel vapors with it,
causing their losses. The separation of surplus air from the fuel
during the climb to altitude considerably facilitates the appearance
of cavitation in the fuel system because of the volume of liberated
air is rather great and can reach several hundreds of liters for every
1000 l of fuel (if one considers the expansion of air as a result of
the decrease in pressure with the gain in altitude).

The liberation of surplus air from the fuel during the gain in
altitude, as a rule, is retarded, especially at a large rate of
climb. At altitudes above 8000 m this can lead to temporary
effervescence of the fuel. The fuel supersaturated with air boils
up especially vigorously during mixing, for example during maneuvers
of the aircraft or when the fuel is pumped from one tank into another.
The temporary cavitation in manifoldes that occurs in this case
causing oscillation of the fuel pressure does not present a practical
danger, only if it is not an occasion for incorrect crew actions.

The solubility in fuel of oxygen, nitrogen, and inert gases
which are components of air, is varied. At 15.5°C the coefficient
of solubility of oxygen in kerosene equals 0.0285, of nitrogen -
0.0157. Owing to this, oxygen dissolves in fuel in a greater pro-
portion than it is contained in air. Therefore the gas mixture that
is liberated from the fuel is richer in oxygen than ordinary air.
The volumetric ratio of nitrogen to oxygen in it comprises 2.07:1,
which in air it equals 3.76:1. This phenomenon increases the limits

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of explosiveness of mixtures formed with fuel vapors.

Furthermore, gas with an increased oxygen content is a more aggressive medium than ordinary air, in the relationship of the corrosion of materials.

4. Effect of Fuel on the Corrosion of the Parts of the Fuel Apparatus and the Engine

When using fuels the corrosion of parts of some units of the fuel system and the engine is observed. Two types of corrosion are distinguished:

liquid-phase corrosion of the units of the fuel system;

gas high-temperature corrosion of the walls of the combustion chamber, the exhaust nozzle, and parts of the gas turbine.

The basic corrosion-active components of fuel during liquid-phase corrosion are some sulfurous and oxygen compounds, and also the water present in the fuel. Among sulfurous compounds, the most corrosion-active are elementary sulfur and mercaptans.

Elementary sulfur causes corrosion mainly of the parts of the fuel apparatus, made from copper alloys. Figure 30 shows the effect of elementary sulfur on the corrosion m_n and the amount of corrosive deposits m_o on antimonous bronze VB-24. The corrosion process is accompained from the beginning by the destruction of the surface of the bronze and then considerable corrosion deposits of a black color are formed on it which subsequently separate themselves from a surface and accumulate in the fuel intthe form of black insoluble deposits. The more elementary sulfur in the fuel, the more intensive these processes develop.

Studies established that the process of corrosion of copper alloys under the influence of elementary sulfur cannot be examined as

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a process which proceeds on the surface of a metal. The basic mass of elementary sulfur from the fuel penetrates deep into an alloy, enters there as the interaction with its components, and destroys its elementar structure.
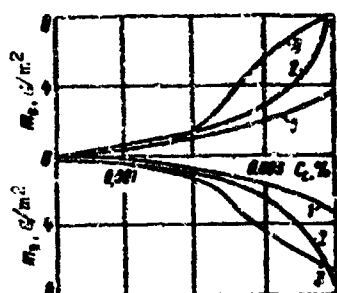
Fig. 30. Dependence of the corrosion aggressiveness of aviation kerosenes on the concentration of elementary sulfur: 1 - Baku; 2 - Groznyy; 3 - from sulfurous oil.

At temperatures of 120-150°C, 50-95% of all the elementary sulfur existing in the fuel can penetrate deep into the bronze.

Serious difficulties during use appear when using fuels, which possess an increased corrosion aggressiveness, as a result of the presence of mercaptan sulfur in them. Most sensitive to the effect of mercaptan sulfur are the bronze and cadmium-plated parts of the fuel apparatus. When operating engines on wide-fraction fuels and lightened kerosene with an increased mercaptan sulfur content the appearance of the corrosion deposits on the bronze parts of the fuel apparatus and the appearance of jelly-like deposits on the cadmium-plated parts of the fuel pump were noted. Part of the corrosion deposits which get into the fuel clog the straight through cross sections of the force pump, and disrupt the operation of the fuel regulators, etc. The corrosion aggressiveness of fuels increases with an increase in the content of mercaptan sulfur in them which is illustrated by the data in Table 8.

At elevated temperatures the corrosion aggressiveness of sulfur compounds is very sharply strengthened. Thus, for instance, with an increase in the temperature of from 95 to 120°C the corrosion of bronze by wide fraction fuel increases by 1.5-2 times.

Table 8. Effect of mercaptan sulfur on the corrosion aggressiveness of wide fraction fuel at 60°C after 100 h.

Sulfur content in the fuel, %		Corrosion, g/m²	
overall	in that a number, mercaptan	copper	bronze VB-24
0,14	0,002	0,8	1,1
0,15	0,005	2,5	3,5
0,15	0,010	3,1	7,6
0,17	0,025	6,2	12,3
0,23	0,050	9,3	14,2

The elevated acid content of the fuel and presence of water in it in many instances intensify the corrosion of the fuel system. Water and water logged fuel cause corrosion of the predominantly steel parts of the fuel system. The corrosion appears in the form of local darkenings, separate sports, a rust, and fine sharp defects on the surface of the metal. In this case brown flakes form in the fuel which consist of an iron hydroxide. These flakes can clog the fuel filters and can also jam up the plunger pairs of the fuel pumps. Table 9 gives data on the effect water logged fuel on its corrosion aggressiveness.

Table 9. Effect of the concentration of water on a corrosion aggressiveness of aviation kerosene.

Fuel	Number of days, after which the corrosion of steels appears				
	20	40	15	38KhA	KhVG
Commercial............	7—10	15—20	15—20	15—20	70—75
Dried................	360	240	270	270	400

The table shows that after drying the fuel its corrosion aggressiveness falls several times.

The presence of sulfur and its compounds in fuels can be the reason for corrosion of the parts of the combustion chambers of engines. During the combustion of fuel in a piston engine sulphuric anhydride (SO_3) is revealed in the products of combustion. When

sulphuric anhydride is dissolved in the water, condensed on the walls
of the engine cylinders, sulphuric acid of a varied concentration is
formed which causes strong corrosion of the cylinder walls, piston
rings, and other parts of the engine. The presence of water vapors
and of carbonic acid in the products of combustion and their condensa-
tion on the cylinder walls of an engine also can be a reason for the
appearance of the corrosion process.

In the combustion chambers of jet engines corrosion of the
combustion chamber walls, nozzles, and parts of the gas turbine is
caused both by sulfurous compounds, and by some metals contained in
the fuel in the form of ashes.

The basic component in the composition of heat-resistant alloys
and steels, from which the combustion chamber, gas turbine, and jet
nozzle are made is nickel. With the burning of all the sulfurous
compounds in the fuel sulfurous gas is formed. Under temperature
conditions above 1000°C sulfurous nickel can be formed which leads to
the formation of nickel eutectics - nickel sulfide. Since the melt-
ing point of this eutectic equal approximately 650°C, it burns down
and causes destruction of the parts.

The metals present in the ashes of fuels pay the part of
catalysts, facilitating the development of the corrosion processes.
The most active metals, instrumental in the development of the
corrosion processes in combustion chambers, are vanadium and sodium.
The mechanism of vanadium corrosion can be presented in the following
manner. The vanadium pentoxide formed after combustion (melting
point 685°C) settles in the liquid state on the metal surfaces of the
gas circuit.

Vanadium possesses a variable valence and under conditions of
high temperature easily returns part of the oxygen to the iron, which
in this case is destroyed, forming oxides. The vanadium pentoxide
converts into tetroxide (with the liberation of atomic oxygen, which
oxidizes iron), but upon contact with the surplus of oxygen in the

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gas circuit again regenerates into pentoxide. Thus, vanadium can play the role of an oxygen carrier - the catalyst of gas corrosion.

5. Antiwear Properties of Aviation Fuels

The durability and reliability of fuel systems of modern and perspective aircrafts depends mainly on the wear resistance of the many slipping and rolling friction pairs that operate in a fuel medium. The wear resistance of friction pairs, as is known, depends on three groups of factors:

the external work conditions of a friction pair: contact stresses, the rate of slipping (or rolling), volumetric temperature;

the material of the surfaces of friction and the geometry of contact: hardness of the materials, the treatment purity, the chemical activity of the materials, etc.;

the properties of the medium in which the friction pair operates.

If one assumes that according to design-technological considerations the first and second group of factors are preset, the the wear resistance of the friction pair depends only on the third group of factors, i.e., on the properties of the medium, its viscosity, oiliness, chemical and physical activity, etc. In the fuel systems of aircraft friction pairs operate in a medium of aviation fuel. Therefore the third group of factors is a combination of the properties of the fuel, which influence the wear resistance of the friction pairs. Subsequently all properties of fuel which influence the wear resistance of a friction pair, we will call by one term - the antiwear properties of the fuel.

The antiwear property of a fuel - this is a combination of its properties, which change the wear of a friction pair that operates in the medium of a given fuel, in comparison with the wear of this

same friction pair in a medium of standard fuel, all other conditions being equal. The antiwear property of a fuel should be evaluated either by the amount of wear of a friction pair, or by the sizes of other parameters, functionally connected with the wear of the friction pair. In other words, the main and determining parameter of the antiwear properties is the amount of wear of the friction pair. The methods of evaluating the antiwear properties of a fuel were described in Chapter II.

A number of fundamental studies by P. A. Rebinder, B. D. Deryagin, A. S. Akhmatov, F. P. Bouden, D. Teybar, G. V. Vinogradov, G. I. Fuks, N. L. Goliy, and others were dedicated to research on the interactions of friction pairs with a liquid medium.

Today the basic directions of the processes taking place in the surface layers of a friction pair upon their interaction with the liquid medium are known. However the processes of the physicochemical interactions of a liquid medium with the surface of friction pairs are so complex, that for a detailed interpretation of them new deep studies are necessary.

Today it is possible to speak reliably about the following processes of the interaction of a liquid medium with the surfaces of friction pairs.

Adsorption from the liquid medium of surface-active molecules and the formation on the friction surfaces of mono- or polymolecular boundary layer, which possesses specific properties different from the properties of the liquid medium and the hard surface. This very thin boundary layer 0.1-1.0 μm thick fulfills the role of a lubricating film and resists direct contact of the friction surfaces. In this case the friction force and the wear of the friction surfaces decreases.

The introduction of separate molecules or groups of molecules

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of a liquid medium into microcracks on friction surfaces or on the
intercrystalline planes of the friction surfaces leads to an easing
of the microplastic deformations of the surface layers, an easing
of the dispersion processes, etc., which in turn leads to an improve-
ment in the breaking in of friction pairs, and to a decrease in the
friction and wear forces.

*The chemical interaction of components of the liquid medium with
the material of the friction surfaces.* The result of such an inter-
action is new chemical substances. Depending on their properties
they can either fulfill the role of thin lubricating layers decreasing
friction and wear, or increase the wear due to intensive crumbling
from the friction surfaces.

The surface layer of the metal possesses great activity because
in the atoms located on the surface, there are free bonds, not
compensated for by neighboring atoms. Thanks to this the surface
of the metal attracts atoms or molecule of various gases and liquid
vapors from the external surrounding medium. As a result thin films
are formed on the surface. The phenomenon of the formation on the
surface of a solid body of thin films of gases, vapors or of sub-
stances dissolved in a liquid is called adsorption. Surface-active
substances, including organic acids, their metallic soaps, alcohols,
and resins possess the greatest capacity for adsorption on solid
surfaces.

A characteristic peculiarity of surface-active substances is
the noncoincidence of the centers of gravity of the positive and
negative charges in their molecules; even in an isolated state there
exist in their molecules two contradictory spacially divided charges.
Figure 31 shows a diagram of the location of the saturated molecules
of a fatty acid (RCOOH) in their coupling with the lattice of a metal.
A saturated adsorption monolayer is formed in this manner from the
closely distributed molecules, oriented parallel to each other and to
the surface of the body. The end of the molecule joined to the metal
is similar to a small magnet, and it is called polar or active.
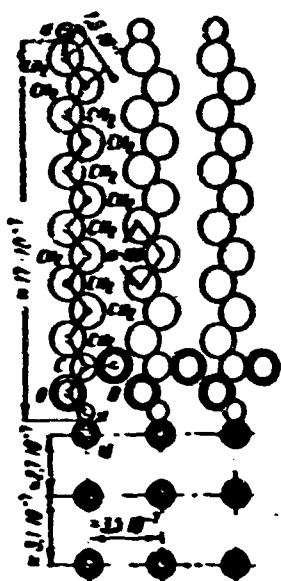
Fig. 31. Diagram of the location of a saturated molecule of a fatty acid in coupling with the lattice of a metal (sizes in millimeters).

In all organic acids and their soaps the carboxyl group COOH is active, in alcohols - the hydroxyl OH, etc. Molecules of the substances adsorbed on the surface of a solid body, possess capacity to move about the surface from places where there is a surplus of them to places where there are not enough of them until the surface is completely covered.

Adsorption is physical and chemical. During chemical adsorption (chemisorption) the polar ends of the molecules connecting with the surface of the body, form a monolayer of their kind of chemical compound on it. The mobility of the molecules as a result of this is greatly limited. Chemisorption unlike physical adsorption has a selective character; it flows with greater intensity in areas of the breakdown of the crystal lattice by impurities or unfilled joints.

In many instances physical and chemical adsorption flow simultaneously, but one of them is dominant. Thus, there are bases for considering that at normal temperatures the adsorption of fatty acids on metallic surfaces has basically a physical character, and elevated temperatures - a chemical one.

Nonpolar saturated molecules of hydrocarbons can also be adsorbed on metallic surfaces. Adsorption in this case occurs under

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the influence of the polarization of nonactive hydrocarbon molecules
by the electrical field of the metal surface. The strength and the
stability of such an adsorption layer is small. It is interesting,
that if we add a small amount (about 0.1%) of a surface-active sub-
stance consisting of nonpolar hydrocarbon molecules into the liquid,
then a rather durable boundary layer will be formed on the surfaces
consisting of a monolayer of surface-active molecules and several
layers of strictly oriented nonpolar molecules of the hydrocarbons
of the solvent (Fig. 32).
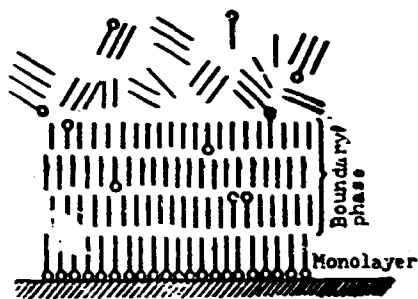
Fig. 32. Effect of an adsorbed
monolayer of polar molecules on
the orientation of the nonpolar
molecules of a solvent.

Boundary layers are found in a specific state of aggregation
different from the solid and the liquid. The structure of boundary
layers in several characteristics recalls the structure of a crystal
solid body. In connection with this it is called quasi-crystalline
(Latin quasic - as if, seemingly).

The boundary layers in a direction perpendicular to the surface
of a solid body possess a very large strength and are able to stand
large specific loads (up to 1000 kg/cm^2). At the same time very
insignificant forces in tangential directions are necessary to shift
one layer relative to another. This peculiarity of the boundary layers
gives to them the properties of good lubricating films. With an
increase in the temperature and upon reaching its critical value
the quasi-crystalline structure of the boundary layer is destroyed,
taking place as if the film had melted. The molecules lose their
capacity for adsorption and disorientation of them occurs. The
temperature of destruction of the boundary layer of fatty acids on
chemically inert metals equals 40-80°C, and chemically active -
90-150°C.

Surface-active molecules, falling a solid surface, occupy the total free surface due to the capacity to travel (to migrate). Travelling about, the molecules penetrate into microscopic cracks on the surface of the division of the grain, into the unfilled joints of the crystal lattice. In addition the free surface energy of the solid body decreases considerably which in turn leads to easing of the plastic current in the surface layer. This action of surface-active substances is known as the effect of adsorption plastification.

Academician P. A. Rebinder detected and studied the effect of absorption plastification for the first time.

Surface-active molecules falling into microscopic cracks of the friction surfaces and reaching places where the clearance width is equal to the size of one-two molecules, try by their pressure to split the crack (Fig. 33). This phenomenon is known by the name of the adsorption-cleaving effect which also for the first time was detected and studied by Academician P. A. Rebinder. It has been calculated that the pressure on the walls of a crack can reach up to 1000 kg/cm^2. The adsorption-cleaving effect of surface-active molecules also leads to easing of the plastic deformations in the surface layer and to a decrease in the strength of a metal. During friction of metals this leads to a better run in of parts and to a decrease in the size of the friction force. However the adsorption-cleaving effect can lead to an increase in the wear of friction pairs due to easing of the processes of scattering of the surface volumes of metal.
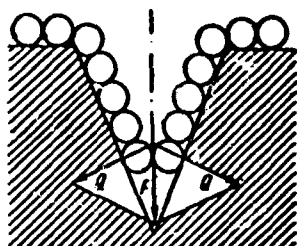
Fig. 33. Diagram of the adsorption-cleaving effect of the polar molecules of grease: F – pressure of the adsorbed layer; Q – cleaving forces.

The liquid medium in which a friction pair works can contain chemically active, in relation to the material of the friction surfaces, substances or elements. As a result of the chemical interaction of components of the liquid medium and the material of the friction surfaces thin films are formed on the friction surfaces. These films can play the role of solid lubricant, avoiding the contact and welding of metals during friction. One of the most widespread chemically active components of a hydrocarbon liquid medium is dissolved oxygen.

In aviation kerosenes 3.67-4.95 cm^3/100 ml can be dissolved. Such a quantity is completely sufficient to have the oxygen actively react with the metal of the friction surfaces forming oxides of these metals.

In fuels there are sulfur-organic compounds, which at high temperatures and pressures upon friction contact can decompose with the liberation of sulfur. Sulfur, reacting with the metal of the friction surfaces forms sulphides. Also chemically active with respect to metal friction surfaces are phosphorus, chlorine, and others.

If the friction pairs operate at high temperatures, large specific pressures, and speeds of a relative movement, then the longevity, reliability, and small wear is provided for only by the correct selection of chemically active components in a liquid medium.

Aviation fuels, a medium in which numerous friction pairs of fuel units operate, contain this or that quantity of surface-active or chemically active substances. The quantity of these substances and their effectiveness depends on the chemical composition of the oil from which the fuel is obtained, the technology of obtaining it, the methods and depths of cleaning. All these factors, apparently, should influence the antiwear properties of this or the other type of fuel.

A substantial improvement in the antiwear properties of fuels can be achieved by the introduction of special additives. However for

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a more correct selection of the raw material, the technology of obtaining, the method of cleaning, the type and quantity of the additives it is necessary to conduct capital studies of the antiwear properties of fuels and their component parts.

The author together with his colleagues conducted a series of investigations to clarify the effect of a number of factors on the antiwear properties of aviation fuels. The investigations were conducted on the laboratory devices described in Chapter II.

Primarily it was necessary to explain as far as possible the differences between different types of fuels, for example, T-1, TS-1, T-7, which are recommended for the same aircraft. It turned out that under the same test conditions these fuels differ substantially according to the antiwear properties.

Under laboratory conditions during slip friction we proposed to evaluate the antiwear properties of fuels with respect to value K, which is found from the following expression:

$$K = \frac{P_{\text{кр}}^{\text{и}}}{P_{\text{кр}}^{\text{э}}} \cdot \frac{H_{\text{э}}}{H_{\text{и}}} \, 100.$$

where K - the indicator of the antiwear properties, %; $P_{\text{кр}}^{\text{э}}$ - critical load of the beginning of gripping of metals under friction in a standard fuel, kg; $P_{\text{кр}}^{\text{и}}$ critical load of the beginning of gripping of metals under friction in the fuel being tested, kg; $H_{\text{и}}$ - wear of the metals in the fuel being tested, mm; $H_{\text{э}}$ - wear of the metals in a standard fuel, mm.

If, for example, we take T-1 fuel as the standard, then for it indicator $K = 100\%$, then for the fuel TS-1 $K = 65\%$, and for fuel T-7 $K = 30\%$. The larger the K indicator, the better the antiwear properties of the fuel. The large difference in the antiwear properties of the fuels T-1, TS-1 and T-7 can be explained by their different fractional and chemical composition. If the composition of the fuel has a large effect on the antiwear properties, then it appears that

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the fuel of one type, but obtained from different deposits of oils will have different antiwear properties.

Figure 34 gives the results of tests of TS-1 fuels obtained from different deposits of oil. As seen, the fuels differ considerably in their antiwear properties both during testing under laboratory conditions according to the K indicator (Fig. 34a), and during testing on stands (Fig. 34b). The very good agreement of the results of the laboratory tests with those of the stand tests should be noted.
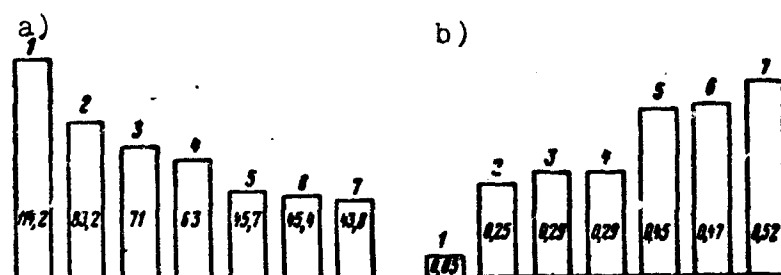
Fig. 34. Antiwear properties of the fuel TS-1, obtained from different oils: a) tests under laboratory conditions according to indicator K; b) tests on stands for wear in mm; 1 - TS-1 - Khabarovsk; 2 - TS-1 - Angara; 3 - TS-1 - Groznyy; 4 - TS-1 - Omsk-Shaimsk; 5 - TS-1 - Novopolotskiy; 6 - TS-1 - Omsk-Tyumen'; 7 - TS-1 - Ryazansk.

Thus, the antiwear properties of aviation jet fuels depend upon their composition, and since the composition of fuels changes depending on the oil deposits, therefore, one type of fuel can have different antiwear properties.

Frequently in practical activity we identify the viscosity of a liquid and its antiwear properties. The greater the viscosity of the liquid, the better the antiwear properties. This is correct only for the hydrodynamic friction regime (see Chapter VIII). For boundary friction the viscosity and antiwear properties are not always identical ideas. In order to show this experimentally, we took several fuels of different and close viscosity and tested them on laboratory devices. The results of the tests are presented in Fig. 35. As seen, the fuels of one level of viscosity can differ in tens and hundreds of ways from

one another in antiwear properties and vice versa, the fuels can possess practically identical antiwear properties, but differ considerably in the level of viscosity. These experiments have persuasively shown that boundary friction is reproduced on laboratory devices, but not the hydrodynamic mode of friction.
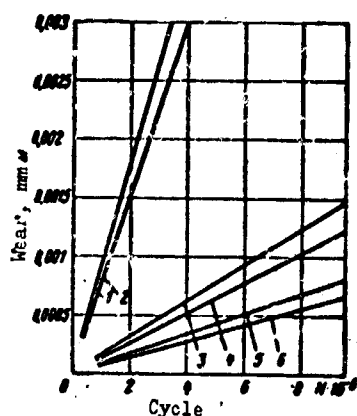
Fig. 35. Antiwear properties fuels of a different viscosity: 1 - undecane deresinified (ν_{20}) = 1.66 cSt); 2 - T-7 (ν_{20} = 1.27 cSt); 3 - naphthenic-paraffin fraction (ν_{20} = 1.87 cSt); 4 - pentodecane (ν_{20} = 3.96 cSt); 5 - T-1 (ν_{20} = 1.64 cSt); 6 - undecane commercial (ν_{20} = 1.7 cSt).

At the same time a correspondence sometimes is observed between the viscosity of a fuel and its antiwear properties. For example, the fuel T-1 is better according to the antiwear properties, than T-7, and its viscosity is greater, The TS-1 fuel has greater viscosity than T-7, and its antiwear properties are better. It is possible to explain this by the fact that viscosity is an indirect index of the amount of high-molecular surface-active organic compounds present in the fuel which considerably increase the antiwear properties due to the adsorption and chemical modification of the surface layers of the friction parts. Let us take the fuels T-1 and T-7 and separate them into narrow ten-degree fractions 140-150°, 150-160°, 160-170°, etc. Let us determine the antiwear properties and the amount of each ten-degree fraction in the fuel (Fig. 36a, b).

Analyzing the results obtained,, it is possible to see that the fuels T-1 and T-7 according to the properties of narrow ten-degree fractions are practically not distinguished between themselves. But they differ considerably in the amount of these narrow fractions.

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Thus, for instance, there are very few of the fractions 230-240° and 240-250° in the fuel T-7 (2.5%), but in the T-1 fuel there is more than 14% of these fractions, i.e., 7 times more. At the same time these fractions (see Fig. 36a) possess very good antiwear properties. There are significantly more of the 160-170° fractions in the T-7 fuel than in the T-1 fuel however the antiwear properties of these fractions are very poor.
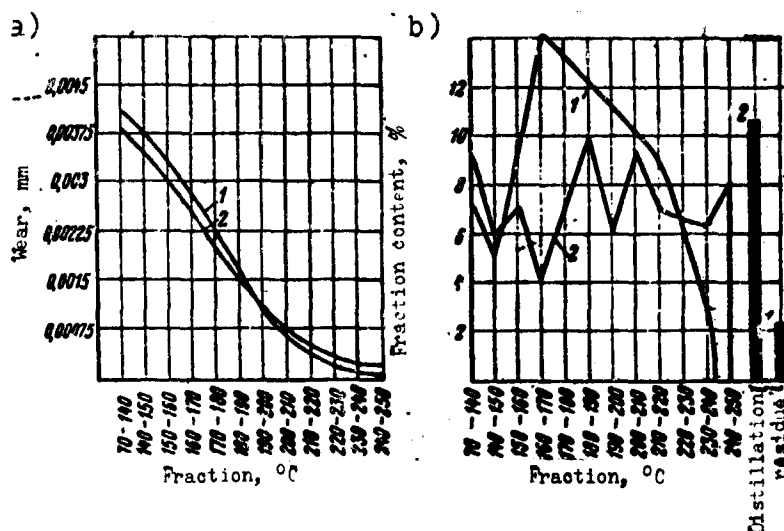
Fig. 36. Antiwear properties (a) and the amount in the fuels T-1 and T-7 (b) of narrow ten-degree fractions: 1 - T-7; 2 - T-1.

Fuel consists of hydrocarbons, heteroatomic compounds (oxygen, sulfurous, nitric), dissolved gases, dissolved water, and mechanical impurities. The greatest effect on the antiwear properties of commercial fuel is shown by the heteroatomic compounds and the dissolved gases. If we remove from the fuel all the heteroatomic compounds in it, then the antiwear properties of such a purified fuel considerably deteriorate.

When fuels are passed through a layer of aluminosilicate they are freed from a considerable part of the heteroatomic compounds (they are deresinated), in this case their antiwear properties considerably deteriorate (see Fig. 35). This is explained by the fact that the

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heteroatomic compounds are very surface-active and are easily adsorbed on the friction surfaces forming durable boundary layers. Furthermore, a considerable portion of them is chemically active and under friction decomposes with the liberation of such elements, as oxygen, sulfur, carbon, and hydrogen in an active form. These elements combined with the metals of the friction surfaces forming oxides, sulfides, carbides, etc., shielding the surfaces from increased wear.

A specific role during the friction of metals in the medium of fuels belongs to the oxygen dissolved in them. The role of oxygen in the processes of external friction without a lubricant is shown in the numerous investigations of Prof. B. I. Kostetskiy. He has proven that during friction oxygen forms oxides with the metals of the friction surfaces, which can either shield them from a wear, or increase the wear depending on the quantity and quality of these oxides.

B. I. Kostetskiy together with the author of this book detected the considerable effectiveness of the natural thin oxide layers on a metal surface during boundary slip friction. It turned out that if we conduct tests in a medium of inert gas, during boundary friction seizing of the samples sets in not right after turning on the machine, but after a certain period of a time necessary for abrasion of the natural oxide film which is found on the friction surfaces. If we substitute air for the inert gas then the process of seizing does not set in at as large a test interval as desired because under these conditions the oxygen in the air combining with the metal of the friction surfaces forms new layers of oxide films in proportion to their wear.

The effect of oxygen on the processes of metal friction in hydrocarbon media has been studied in the capital works of Prof. G. V. Vinogradov. They showed for the first time that a hydrocarbon medium can transport oxygen to the friction surface by means of oxidation of the hydrocarbons and their subsequent decomposition on the friction surfaces with the liberation of oxygen in an active form.

A relatively large amount of oxygen (up to 25% by volume), can be dissolved in jet fuel, and, therefore, its effect on the antiwear properties should be considerable. The processes of friction depending on the oxygen content develop differently during rolling and slipping (Fig. 37). During rolling the deeper the cleaning of the fuel from oxygen, the better its antiwear properties become. During slipping an optimum concentration of oxygen exists at which the antiwear properties of the fuel will be the highest. A decrease or increase in the concentration of oxygen in comparison with the optimum leads to a deterioration of the antiwear properties of the fuel.
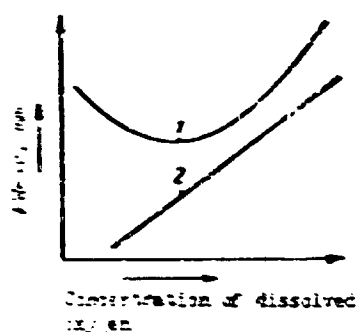
Fig. 37. Dependence of the wear of metals in T-7 fuel on the concentration of dissolved oxygen: 1 - during slip friction; 2 - during rolling friction.

The hydrocarbons in the composition of aviation fuels are divided into alkanes of a normal structure and isostructure, naphthenes, and aromatics (see Chapter I). Study of the antiwear properties of the separate groups of hydrocarbons was accomplished by testing a mixture of individual hydrocarbons of equal viscosity. The alkanes of a normal structure were introduced to a mixture of pentadecane with n-heptane, the naphthenes - to a mixture of cyclohexane with a decalin, the aromatics - to a mixture of isopropyl benzene with α-methylnaphthalin. The viscosity of every mixture was selected as equal to 1.5-1.6 cSt at 20°C.

The results of the tests of the hydrocarbon mixtures during slip friction are presented in Fig. 38. The antiwear properties of the hydrocarbons change considerably depending on whether oxygen is present in the contact zone. In testing without preliminary scavenging of the fuel with inert gas hydrocarbons are located in the following

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diminishing order by their antiwear properties: aromatics-naphthene-
alkanes. If we conduct tests with preliminary scavenging of the fuel
with inert gas, i.e., under conditions where oxygen is absent, then
the hydrocarbons are located in the same order by the antiwear
properties, however the character of wear in some hydrocarbons changes.
This is explained by the fact that hydrocarbons have a different
capacity for oxidation and the products of oxidation are the carriers
of the antiwear properties. The test conditions exert a considerable
effect on the antiwear properties of aviation fuels - the rate of
slip, load or contact, the volumetric temperature of the fuel. In
fuel units the friction pairs do not operate under constant conditions
because the rate of slip or rolling, contact stresses or the volumetric
temperature change.
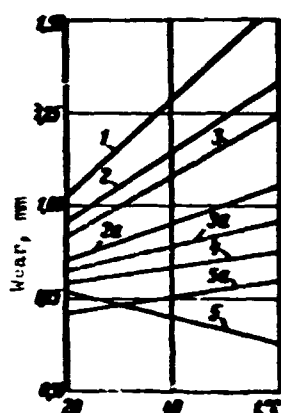
Fig. 38. Antiwear properties of the hydrocarbon
in the composition of fuels: 1 - T-7 without
scavenging; 2 - n-paraffin without scavenging; 2a -
n-paraffin with scavenging; 3 - naphthene without
scavenging; 3a - naphthene with scavenging; 4 - TT
without scavenging; 5 - aromatic without scavenging;
5a - aromatic with scavenging.

In order to study the effect on the antiwear properties of fuels
of the test conditions special experiments were conducted. Figure 39
shows the dependence of the antiwear properties of fuels on contact
loadings. With an increase in contact loadings the wear increases,
and upon reaching a determined load during slip friction seizing of the
the metals occurs with a sharp increase in wear. During rolling
friction the wear is directly proportional to the load, if only this
load does not cause noticeable plastic deformations of the surface
layers of the metals.

With an increase in the rate of slip the wear of metals in a
medium of fuels decreases which is evident from Fig. 40. A similar
dependence also takes place during rolling friction.
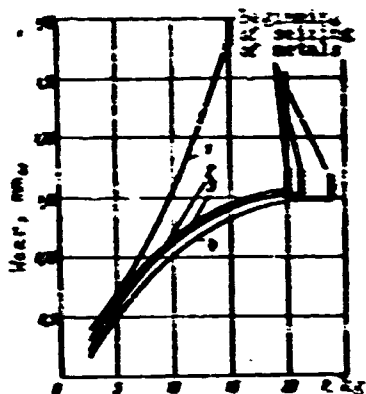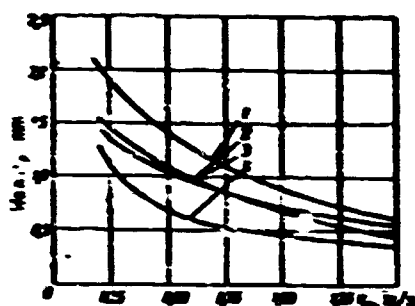
Fig. 39.   Fig. 40.

Fig. 39. Dependence of the wear of metals
in fuels on the contact loadings at U_{cx} =
= 1.44 m/s and t = 20°: 1 - T-7; 2 -
naphthyl; 3 - TS-1; 4 - T-1.

Fig. 40. Dependence of the wear of metals
in fuel on the rate of slip at P = 2 kg;
t = 20°C: 1 - T-7; 2 - naphthyl; 3 - TS-1;
4 - T-1.

Studies of the dependence of the antiwear properties of aviation
fuels on the volumetric temperature present a special interest. In
the fuel tanks of supersonic transport aircraft fuel is heated to
temperatures of 120-150°C. Such temperatures will be reached because
of aerodynamic heating in supersonic flight. The antiwear properties
of aviation fuel change with a change in the volumetric temperature,
moreover these principles are unequal for rolling friction and slip
friction.

During rolling friction (Fig. 41a) the wear of metals in fuel
with an increase in the volumetric temperature at first increase and
reaches its maximum value, and then it drops sharply and at tempera-
tures of 130-140°C it becomes equal to the wear at a temperature of
20°C. For every type of fuel their temperatures of maximum wear
exist. Thus, for fuel T-1 this temperature is equal to 90°C, for
T-7 - 60°C, T-6 - 90°C, naphthyl - 75°C, TS-1 - 67°C. Such a
character of the dependence of wear on the volumetric temperature of
the fuel is explained by two processes: with an increase in the
temperature from 20° to the temperature of maximum wear an increase

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in wear occurs because of the oxidation of the friction surfaces with the dissolved oxygen. With an increase in the temperature the chemical activity of the fuel increases, and at determined temperatures the components of fuel, entering the chemical interaction with the oxygen and the metal, form films of chemical compounds on the surfaces, moreover the effectiveness of these films is higher, the higher the temperature of the fuel. At temperatures of maximum wear the lubricating effectiveness of the films of chemical compounds increases so, that with a further increase in the temperature the wear decreases.
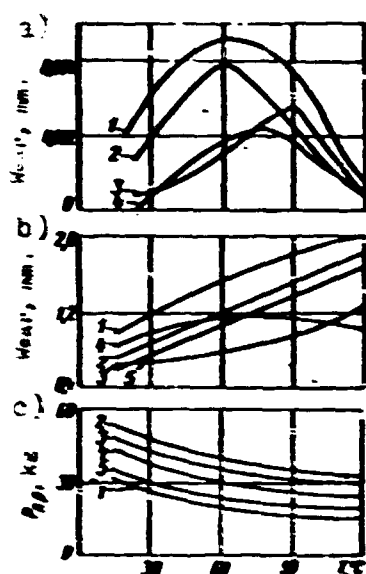
Fig. 41. Dependence of the antiwear properties of fuels on the volumetric temperatures: a) wear during rolling: 1 - T-7; 2 - TS-1; 3 - T-1; 4 - naphthyl; b) wear during slipping: 1 - T-7; 2 - TS-1; 3 - T-1; 4 - T-7 + PMAM; 5 - naphthyl; c) critical load during slipping: 1 - T-7; 2 - T-1; 3 - T-7 + PMAM; 4 - TS-1; 5 - naphthyl.

During slip friction in the range of temperatures of fuel of 20-120°C the wear of metals in all fuels is practically directly proportional to the volumetric temperature and only at temperature above 120°C is a bend in the curve and a decrease in the wear marked (Fig. 41b). In this case the same processes as during rolling friction takes place, however the lubricating capacity of the films of chemical compounds is attained at higher temperatures. If we chemically activate the fuel for example, with the addition of an additive then the dependence of wear on the temperature during slip friction will have a clearly expressed maximum (see Fig. 42b).
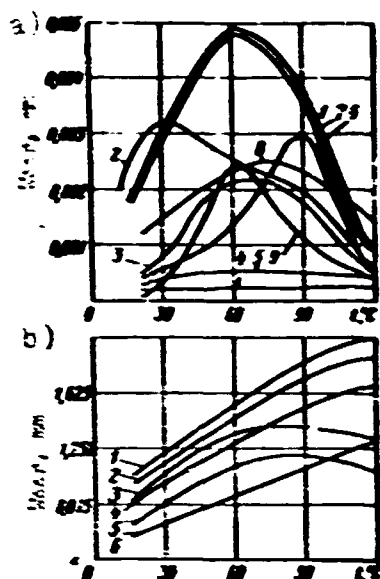
Fig. 42. Antiwear properties of additives:
a) wear during rolling; b) wear during slipping:
1 - T-7; 2 - T-7 + ionol (0.03%); 3 - T-7 + TP
(0.03%); 4 - T-7 + Akor-1 (0.03%); 5 - T-7 +
+ PMAM-2 (0.03%); 6 - T-7; 7 - T-7 + ethyl
cellosolve (0.3%); 8 - T-7 + ethyl cellosolve
(0.3%); 8 - T-7 + TGP (0.03%); 9 - T-7 + MS-20
(1%).

The critical load of seizing of metals in jet fuels also depends
on the volumetric temperature. With an increase in the temperature
the critical load decreases (Fig. 41c).

Various additives (antioxidants, antistatics, low-temperature,
etc.) are added to modern jet fuels to improve their operational
properties. Furthermore special antiwear additives are being
developed. An additive of any designation besides antiwear, added to
a fuel, should either not change its antiwear properties, or should
improve them. An antioxidant additive ionol, a low-temperature -
ethyl cellosolve and TGP, antiwear - TP and PMAM-2, MS-20 oil, and
an antistatic Akor-1 were tested.

The results of the tests of these additives are given in
Fig. 42. All the additives possess to one degree or another antiwear
properties. The most effective were the antistatic additive Akor-1
and the antiwear additives PMAM-2 and TP. The effectiveness of the
additive depends on its concentration in the fuel. For the additives
the effectiveness of their action increases only to a determined
concentration, whereupon it does not change. For the additives
ionol and Akor-1 the effectiveness of action at first increases, and
after reaching a maximum value it drops, i.e., the concentration of
the greatest effectiveness of action exists. And finally for some

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additives the effectiveness of their action is directly proportional to the concentration.

During the study of the antiwear properties of aviation fuels it is necessary along with a study of the above described dependences to study the mechanism of the interaction of fuel with the metals of the contacting surfaces. Numerous observations of the friction surfaces, a study of the composition of the products of wear, and the processes which take place in the thin surface layers of the metals, make it possible to form the following general diagram of the interaction of fuels with metals in the process of friction. As soon as a metallic sample is immersed in fuel, surface-active molecules of heteroatomic compounds (oxygen, sulfurous, nitride) are adsorbed on its surface and molecular oxygen also forms a thin boundary layer. This layer can absorb the relatively large loads which are normal for friction surfaces and is easily deformed with the application of tangential stresses. When two metal surfaces come in contact a boundary layer of adsorbed molecules will be found between them. If the contact load, the rate of relative movement, and the volumetric temperature of the fuel are small, then the thin boundary layer plays the role of an effective lubricant, and the surface layers of the metal oxides undergo basically an elastic deformation, moreover the deformation is enveloped by the very thin oxide layers. With repeated elastic over-deformation of the oxide layers fatigue failure of them occurs and at the place of the destroyed oxides new ones are formed as a result of the oxidation of the metal by the oxygen always present in the fuel or being liberated upon decomposition of the heteroatomic oxygen compounds.

An increase in the load, rate, or temperature leads to the fact that the boundary film is torn and contact of the pure solid surfaces occurs with the formation of bridges of adhesion, and also a mechanical meshing of the unevennesses of one friction surface with another. In this case along with elastic deformations, plastic deformations of the surface layer metal appear. Considerable local heating of volumes of the metal appear. The more metal enveloped by plastic deformations,

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the greater the temperature of the surface layer will be. If there are surface-active compounds in the fuel then plastic deformation is facilitated and concentrates in a very thin surface layer (the P. A. Rebinder effect). Plastification of the surface layers occurs, the load is distributed more evenly over the area of contact. At the same time during the plastic deformation of a metal and its heating the chemical reactions between the components of the fuel and metal take place at a greater speed. Layers of chemical compounds possessing the properties of a solid lubricant are formed on the friction surfaces. With repeated elastic and plastic over-deformation these layers are destroyed and new ones form in their places. A further increase in the load leads to even greater plastic deformations of the metal of the surface layers, and therefore, and to a greater growth in the temperature. In this case the thickness of the layers being formed increases. The greater the thickness of the films of chemical compounds, the less their fatigue durability; under repeated over-deformations they are quickly destroyed and more intensive wear occurs.

With an increase in the rate of slip and rolling the thickness of the surface layer of the metal, subjected to plastic deformations decreases because the thickness of the layers of chemical compounds being formed increases. With a decrease in the thickness of the deformed layer its durability increases, which leads to a decrease in wear.

An increase in the temperature of the fuel also influences the thickness and properties of the surface films being formed. Up to determined temperatures the properties and thickness of these films are such, that the wear increase, but with higher temperatures it decreases.

Thus, during the friction of metals in fuel two processes occur: the formation and the growth of surface films, which are oxides, sulfides, and carbides of the metal and the fatigue failure of these films during repeated over-deformation. The intensity of wear in every concrete case is determined by the properties and the thickness of the surface films being formed and by their fatigue durability.

Graphically this process can be shown in the following manner (Fig. 43): in the first period from τ_0 to τ_1, the formation and growth of the surface film takes place up to a balanced thickness, after which the film operates from τ_1 to τ_2, then its destruction sets in (from τ_2 to τ_3) and the cycle is repeated.
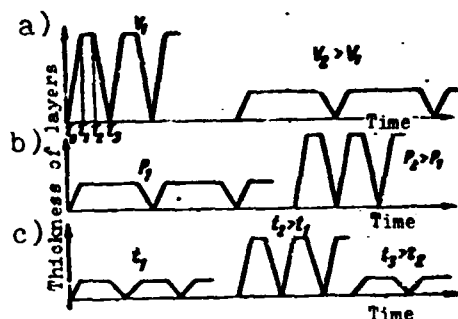
Fig. 43. Diagram of the formation and destruction of surface films during a change in: a) rate; b) load; c) temperature.

The change in the rate (Fig. 43a), load (Fig. 43b) and temperature of the fuel (Fig. 43c) differently influences the thickness and durability of the surface films which also causes a different wear intensity of the metals when these factors change.

The friction of metals in fuel is accompanied by the formation of products of wear, oxidation, and by splitting of the molecules of fuel. If a roller or slip bearing operates for a short time in an amount of fuel, its initial properties will change substantially. The color changes, the content of mechanical impurities increases, and the products of deep oxidation and polymerization appear. The depth of these changes depends both on the operating conditions of the bearing (rate, load, temperature, duration), and on the properties of the fuel. Some fuels are very stable under these conditions and, possessing good antiwear properties, do not change their initial properties during the friction of metals in their medium. Other fuels are slightly stable and, possessing good antiwear properties, change their initial properties considerably. Such fuels are little suitable for aircraft.

There exists the idea of thermal stability (see Chapter VI),

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i.e., the capacity of a fuel to retain its initial properties under the pressure of high temperature on it. Unlike this, the capacity of a fuel to retain its initial properties during the friction of metals in its medium can be called contact-thermal stability.

Thus, a fuel should possess not only good antiwear properties, but also good contact-thermal stability. The contact-thermal stability is determined on the same devices, on which the anitwear properties of a fuel are evaluated (see Chapter II). After a determined condition of friction the fuel is poured out from the chamber and undergoes an analysis. The change in the basic properties of the fuel also serves as the index of contact-thermal stability.

6. The Influence of the Fuel Properties on the Process of Carburetion

Combustion - this is the process of the rapid oxidation of the combustible components in a fuel accompanied by the liberation of heat energy. The products of complete oxidation are, as a rule, gaseous incombustible substances (CO_2, H_2O and others).

Oxidation reactions are a series of repeating links. As a result of these reactions active particles are formed, free radicals. In order that oxidation takes place in the form of combustion, there should be conditions for the rapid movement of active particles and for branching of the reaction chains. Such conditions exist only in a gas medium, therefore the evaporation of fuel and the formation of a mixture of its vapors with air (a combustible mixture) always precedes the beginning of combustion.

For the best dispersion fuel is supplied to the combustion chamber of a gas-turbine engine with the aid of centrifugal sprayers under a pressure of 50 kg/cm^2 and greater. The fuel leaves the injector at a speed of about 30 m/s, forming a jet of finely divided fuel. Dispersion of the liquid fuel is accompanied by the sharp

increase in the size of the surface of the fuel droplets and thus depends on the coefficient of surface tension, the size of which for some fuels is given in Table 10.

Table 10. Coefficient of the surface tension of some fuels, dyn/cm^2 at a temperature.

Fuel	20°C	40°C
Aivation gasoline	21	19
Wide fraction type fuel..............	22	20
Aviation kerosene	26	24

The lower the coefficient of surface tension of the fuel, the better the condition of carburetion. The rate of evaporation of the smallest droplets of atomized fuel and condition of carburetion to a considerable extent are determined by the temperature and the turbulence of gases in the heated zone, into which the droplets of fuel fall.

The fractional composition of the fuel exerts a large influence on the processes carburetion. For a better carburetion it is advisable to have fuels of a light fractional composition. The existing types of jet fuels used in the Soviet Union and abroad, have the fractional composition, given in Table 11, providing for a rapid and complete carburetion process.

Table 11. Fractional composition of some fuels.

Boiling out of fuel, %	Temperature of boiling out, °C			
	T-1	TS-1	1R-5	1R-4V
10	175	165	200	121
50	225	195	223	188
90	270	230	254	243
98 (end of boiling)	280	250	288	288

A substantial role in the process of a carburetion is played by the pressure of the fuel vapors at high temperatures. In the front

part of the combustion chamber of gas-turbine engines the temperature of the air at the combustion chamber inlet reaches 300°C, the pressure of the saturate vapors of aviation gasoline - 25 kg/cm^2, of kerosenes - more than 5 kg/cm^2. The higher the pressure of the fuel vapors, the greater their rate of vaporization and the better the carburetion.

7. The Influence of the Properties of Fuel on Starting an Engine

A group of so-called starting properties of a fuel besides its structural peculiarities exert a considerable influence on the starting of an engine.

Under the starting properties of a fuel we mean its capacity for ignition by an electrical spark plug and the capability to bring an engine to a steady operating condition with its help. In this case the starting fuel after ignition should give sufficiently steady and intensive combustion in order to provide for ignition of the basic part of the fuel. Ignition of the combustible mixture basically is determined by:

the limits of ignition according to the concentration of fuel vapors in the air;

the minimum limiting pressure of the combustible mixture;

the minimum energy required for ignition of the combustible mixture (the energy of the electrical spark);

the temperature of spontaneous combustion of a combustible mixture;

the period of ignition delay;

the capability of distributing the flame about a combustible mixture;

the degree of fuel dispersion;

the volatility of the fuel;

the temperature conditions and the speed of the air.

The highest and lowest limits of ignition of a mixture are distinguished. The highest limit of ignition of a mixture is called that content of fuel vapors in air for which a further increase in them makes the mixture noncombustible. The lowest - that content of fuel vapors in air, at which their further decrease makes a mixture non-combustible. The content of fuel vapors in air can be expressed in percentages of the volume of a combustible mixture, in grams per 1 m^3 of a combustible mixture, and with the aid of the coefficient of excess air α (Table 12).

Table 12. Limits of the ignition of combustible mixtures at 20°C and 760 mm Hg.

Fuel	Highest			Lowest		
	%	g/m^3	α	%	g/m^3	α
Aviation gasoline......................	3,04	123,4	0,675	1,83	74,4	1,130
Automobile gasoline....................	2,58	121,0	0,709	1,67	78,4	1,100
Benzene................................	2,84	119,0	0,798	2,00	73,0	1,140
Isooctane..............................	2,30	116,7	0,718	1,61	82,1	1,030

The wider the limits of ignition of a combustible mixture, the better the starting properties the fuel has.

The molecular weight of a fuel exerts a considerable influence on the limits of ignition. Figure 44 gives the limits of ignition for combustible mixtures of individual hydrocarbons which differ in molecular weight. As seen from the figure, with an increase in the molecular weight from methane (1) to hexane (6) the limits of ignition expand considerably.

The limits of ignition depend on the structure of the hydrocarbon

molecules. The widest limits of ignition are observed in unsaturated hydrocarbons which possess double and triple bonds in a molecule (Fig. 45).

Fig. 44.   Fig. 45.

Fig. 44. Dependence of the limits of ignition of a combustible mixture on the molecular weight of a hydrocarbon: 1 - methane; 2 - ethane; 3 - propane; 4 - butane; 5 - pentane; 6 - hexane.

Fig. 45. Dependence of the limits of ignition of a combustible mixture on the structure of the molecules of hydrocarbon: 1 - acetylene; 2 - propylene oxide; 3 - isopentane.

Acetylene (1), having a triple bond in a molecule, possesses the widest limits of ignition. Isopentane (3), which is a representative of the saturated order of hydrocarbons has the narrowest limits of ignition.

The pressure under which the mixture is found exerts a large influence on the limits of ignition. As seen from Figs. 44 and 45, with a decrease in the pressure of a mixture the limits of ignition of fuels become narrow and lower than a certain pressure characteristic for every fuel and called the minimum limiting pressure; ignition of the mixture from an outside source does not occur.

Besides the concentration limits of ignition, the flammability of a combustible mixture is characterized by the minimum (critical)

molecules. The widest limits of ignition are observed in unsaturated hydrocarbons which possess double and triple bonds in a molecule (Fig. 45).

Fig. 44.   Fig. 45.

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Besides the concentration limits of ignition, the flammability of a combustible mixture is characterized by the minimum (critical)

energy of an electrical spark. The fact is that not any spark discharge in a combustible mixture causes it to ignite, although the temperature of such a discharge is measured in thousands of degrees. For ignition and the creation of a self-sustaining combustion reaction a determined minimum spark discharge energy is necessary, which depends on the chemical composition of the fuel, and also on the temperature and pressure (Fig. 46). From the figure it can be seen that the minimum energy of a spark for ignition with a decrease in pressure of from 1 to 0.2 kg/cm^2 grows almost 10 times. With an increase in the temperature of the mixture of from 200 to 400°K, i.e., 2 times, the minimum energy of the spark decreases more than 15 times.
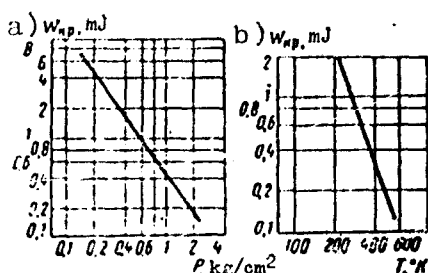
Fig. 46. Dependence of the critical energy of ignition $W_{кр}$ on: a) the pressure at $t = 23°C$; b) the temperature at $p = 1$ kg/m^2.

Figure 47 shows the dependence of the critical energy of ignition on the chemical composition of the fuel. The more atoms of carbon in a molecule of fuel, the wider the limits of ignition it has with less critical energy.
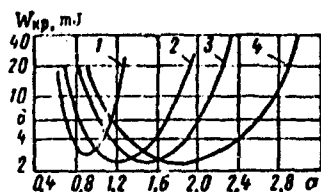
Fig. 47. Dependence of the critical energy of ignition on the chemical composition of the hydrocarbons and composition of the combustible mixture: 1 - methane; 2 - ethane; 3 - butane; 4 - heptane.

One of the important characteristics of fuel which makes it possible to judge its starting properties and the stability of the combustion process, is the temperature of spontaneous combustion of the fuel vapors, i.e., the temperature at which spontaneous combustion of a combustible mixture occurs without contact with an open flame. The process of spontaneous combustion of a combustible mixture is found

Then the amount of heat given off by the reaction

$$q_1 = V \frac{Q}{M} k a^n E^{-\frac{E}{RT}}$$

or

$$q_1 = V A a^n E^{-\frac{E}{RT}}.$$

On the other hand, the amount of heat led away from the reaction space through the surface of the division agrees with the known law of heat transfer

$$q_2 = a(t_1 - t_0) F.$$

where a – the coefficient of heat transfer, cal/(m^2·h·deg); t_1 – the temperature of the reactive substance, °C; t_0 – the temperature of the surrounding medium, °C; F – the surface of heat transfer, m^2.

Thus, the conditions of spontaneous combustion can be expressed mathematically in the following manner:

$$V A a^n E^{-\frac{E}{RT}} > a(t_1 - t_0) F.$$

From the conditions of spontaneous combustion it follows that spontaneous combustion of a system will occur at a lower temperature t_1, the higher the initial temperature, the concentration of reactive substance a, or vapor pressure p, and the greater the volume of reactive substance, because of this case the heat loss into the surrounding medium is lower.

Thus, the temperature of spontaneous combustion is not a physical constant, but depends on the conditions of the experiment.

To determine the temperautre of spontaneous combustion of a combustible mixture the instrument whose diagram is shown in Fig. 48 can be used. The procedure of work consists of that a determined

quantity of fuel is put into a heated quartz bulb and the time is recorded from the moment the fuel is put in to ignition, and the temperature at which it occured. The time in seconds from the moment the fuel is put into instrument to the ignition of its vapors is called the ignition delay period. The ignition delay period characterizes the preflame oxidizing processes and depends on the chemical composition and the structure of the hydrocarbons. Table 13 gives the minimum temperatures and the spontaneous combustion delay periods of combustible mixtures of various fuels at an atmospheric pressure of 742 mm Hg.

Table 13. Minimum temperatures and periods of delay of the spontaneous combustion of a combustible mixtures of some fuels.

Fuel	Temperature of spontaneous combustion, °C	Period of delay spontaneous combustion, s	Fuel	Temperature of spontaneous combustion, °C	Period of delay spontaneous combustion, s
Ethane	515	10	Cyclohexane	200	206
Butane	405	6	Benzene	562	32
Pentane	287	10	Aviation		
Heptane	223	101	kerosene	229	210
Octane	220	132	IR-1	228	120
Isooctane	418	27	IR-3	238	187
			IR-4	242	185

Fig. 48. Diagram of an instrument for determining the temperature of spontaneous combustion: 1 - electric heater; 2 - quartz flask; 3, 4, 5 - lid; 6, 7, 8 - thermocouple; 9 - furnace; 10 - heat insulation; 11 - casing; 12, 13 - supports; 14, 15 - contacts; 16 - furnace support.

In all fuels the temperature of spontaneous combustion of combustible mixtures rises with a decrease in the pressure (Table 14).

Table 14. Minimum temperature of spontaneous combustion of combustible mixtures depending on the pressure.

Fuel	Temperature of spontaneous combustion, °C, at pressure, mm Hg		Fuel	Temperature of spontaneous combustion, °C, at pressure, mm Hg	
	742	370		742	370
1R-4.............	242	444	1R-1.............	228	462
1R-3.............	238	449	100/130.........	440	553

The volatility and degree of dispersion of the fuel under determined conditions can have a greater influence on starting an engine, than its chemical composition. The voltatility is characterized by the fractional composition of the fuel, i.e., by the temperature that 10% of it boils out. The lower this temperature, the easier it is to start the engine. Thus, aviation gasoline with a 10% boiling out temperature of 71°C provides easy starting of an engine at temperature to -60°C, and when using kerosene with a 10% boiling out temperature of 175°C engine starting already at a temperature of -40°C is difficult.

With a decrease in the temperature the viscosity also increases and therefore, is dispersion hampered. Thus, gas oil with a viscosity of 15 cSt at 20°C already at a temperature of -7°C absolutely does not provide the dispersion necessary for starting. Kerosene with a viscosity of 3 cST at 20°C provides satisfactory dispersion at a temperature of -50°C. Gasoline provides the dispersion necessary for a starting at any temperatures.

The average size of droplets of atomized fuel is approximately inversely proportional to the square of the pressure, at which dispersion occurs:

$$d_{cp} \simeq \frac{1}{p^2}.$$

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The higher the degree of dispersion, the easier the fuel will ignite because the surface of vaporization increases, and the expenditures of energy and time of heating and vaporization of the individual droplets decreases. Heavy fuel with a low pressure of saturated vapor requires a greater degree of dispersion to ignite it, i.e., a greater pressure in front of the injector (Fig. 49). If 10% aviation gasoline boils away before 80°C, then a pressure in front of injector of 3 kg/cm^2 is necessary for satisfactory ignition. Aviation kerosene, 10% of which boils away before 160°C ignites satisfactorily at a pressure of 9 kg/cm^2.
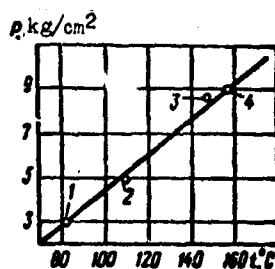
Fig. 49. Dependence of the pressure of the fuel in front of the injector on the 10% boiling out temperature of the fuel: 1 - aviation gasoline; 2 - mixture of 60% aviation kerosene and 40% gasoline; 3 - mixture of 95% aviation kerosene and 5% gasoline; 4 - aviation kerosene.

During starting heavy fuel can be partially separated in a liquid-droplet state on the walls of the combustion chamber. As a result of this an accumulation of fuel occurs which then can suddenly ignite and which can lead to overheating of the engine.

8. Influence of the Properties of Fuel on the Rate and Stability of Combustion

The process of combustion in jet engines takes place in a high-speed air flow, in this case its velocity considerably exceeds the velocity of the standard distribution of flames upon the combustion of hydrocarbons. With the sharp changes in the operating condition of an engine disruptions of the flames can occur. Burning, during which frequent disruptions of the flames occur is called unstable. The process of burning can be described by a standard rate of

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distribution of the flames about the combustible mixture, which depends
on the structure and the molecular weight of the hydrocarbons.
Figure 50 gives the dependences of the standard rate of distribution
of flames V_H on the composition of the fuel-air mixture (α) for
individual hydrocarbons, possessing different molecular structure. As
is evident, other conditions being equal aromatic hydrocarbons (1)
possess the greatest rate of distribution of flames, paraffin (3) -
the least. The greatest rate of distribution of flames is attained
with enriched mixtures: for aromatics at α = 0.6-0.65, for naphthenics
and paraffins at α = 0.85.
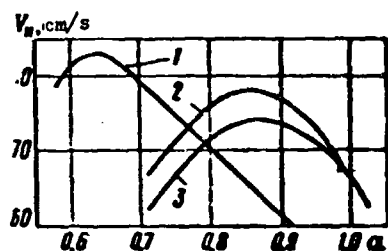
Fig. 50. Dependence of the standard rate of
distribution of flames on the coefficient of
excess air: 1 - benzene; 2 - cyclohexane;
3 - hexane.

The rate of distribution of flames depends on the pressure
at which the process of burning occurs. In lowering the pressure
below atmospheric, the rate of burning at first increases somewhat,
then it falls. The standard rate of distribution of flames depends
also on the temperature of the combustible mixture, to which the
flame is extended. Figure 51 gives the dependence of the standard
rate of distribution of flames on the temperature of a combustible
mixture of n-heptane. As is evident, the rate of distribution of
flames increases with an increase in the temperature according to
linear law. This character of dependence is also retained for other
classes of hydrocarbons, in this case only the angle of slope of the
straight line relative to the axis of abscissa changes. A large effect
on the standard rate of distribution of flames is exerted by the
energy of activation, the higher the rate of standard distribution of
flames (Table 15).
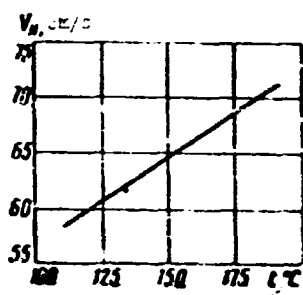
Fig. 51. Dependence of the standard rate of distribution of flames on the temperature of a combustible mixture of n-heptane.

Table 15. Dependence of the standard rate of distribution of flames on the energy activity.

Hydrocarbon	Energy of activation, cal/mole	Rate of distribution of flame, cm/s	Hydrocarbon	Energy of activation, cal/mole	Rate of distribution of flame, cm/s
Acetylene...........	90,000	174.0	Ethane...........	26,000	40.1
Ethylene...........	24,000	68.2	Isopentane.......	27,000	36.6

Movement of the front of flames during turbulent burning in a perpendicular direction to its surface is called the turbulent rate of distribution of flames. It depends upon the physicochemical properties of the combustible mixture and the aerodynamic conditions, which characterized by the Reynolds number:

$$v_r = v_u \sqrt{1 + k\,Re}, \quad \text{or} \quad v_r = v_u \sqrt{1 + \frac{\varepsilon}{a}},$$

where k - the coefficient, considering the condition of combustion; ε - the coefficient of turbulent diffusion; a - the molecular coefficient of thermal conductivity; Re - the Reynolds number.

Figure 52 graphically represents the dependence of the turbulent rate of distribution of flames on the Reynolds number for individual hydrocarbons. As evident from the graph, the rate of distribution of flame due only to turbulence can be increased from 147 to 320 cm/s in acetylene, from 70 to 120 cm/s in ethylene, and from 45 to 55-60 cm/s in propane.

The stability of burning is called the capacity to retain a front of flame during burning with various deviations from the standard

condition both on the side of lean and rich mixtures. The condition
of stabilization of a flame in an air-breathing jet engine is the
equality of the rate of distribution of flame and the rate of flow
in the combustion chamber.
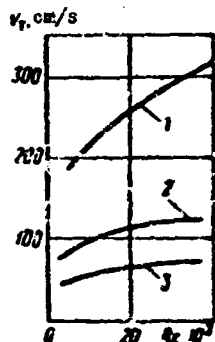
Fig. 52. Dependence of the turbulent rate of burning
of combustible mixtures on the Reynolds number: 1 -
acetylene (V_H = 147 m/s); 2 - ethylene (V_H = 45 cm/s).

In an air-breathing jet engine part of the fuel burns as a
result of spontaneous combustion because as a result of turbulence
separate volumes of the cold combustible mixture fall into the jet
of flame and are heated to a temperature exceeding the temperature of
spontaneous combustion of the mixture. The greater the portion of
fuel that burns as a result of spontaneous combustion of the mixture,
the higher the rate of combustion of the mixture in the engine. There-
fore, to increase the rate of combustion to the limits which provide
for stabiliztion of the flame, it is necessary to increase the degree
of flow turbulence of the combustible mixture which is achieved by
the distribution of poorly streamlined bodies in the path of the
flow.

The consequence of the great influence of spontaneous combus-
tion of a fuel on stabilization of the burning process is a sharp
dependence of the limits of steady burning in air-breathing jet
engines on the chemical composition of the fuel. Figure 53 gives the
results of a study of the effect of the chemical composition of a
fuel on the limits of steady burning. From these data it follows,
that at low fuel temperatures paraffin hydrocarbons are characterized
by the greatest limits of steady burning and aromatic hydrocarbons
by the lowest. With an increase in temperature the limits of

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stabilization of the aromatic hydrocarbons increase, and those of
the paraffin and naphthenic decrease or remain constant. The limits
of steady burning are a characteristic of the capabilities of fuel
to stabilize a flame. The wider the limits of steady burning, the
better the conditions for stabilization of the flame and the more
reliable the operation of an engine under various conditions.
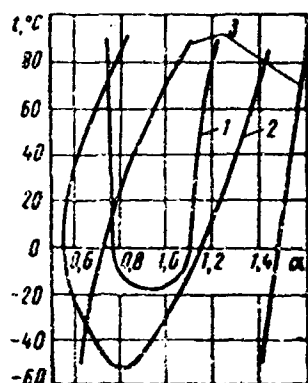
Fig. 53. Dependence of the limits
of burning stability on the chem-
ical composition of the hydro-
carbons. 1 - aromatic; 2 -
naphthenic; 3 - n-paraffin.

9. Influence of the Properties of Fuel on Carbon Formation in an Engine

During the combustion of hydrocarbon fuels the liberation of
dispersed particles of carbonaceous substances, close in composition
to carbon is observed. The solid particles formed during burning
are carried off with the products of combustion and in a large con-
centration they can be noticed in the form of smoke. Part of the
solid emissions is deposited on the surfaces of the combustion
chamber in the form of a carbon deposit. The formation of a carbon
deposit in an engine depends on the following properties of the fuel:
the fractional and chemical composition, density, resinous substances
content, sulfur, and other impurities. Furthermore, carbon formation
depends on the design of the combustion chamber and on the completeness
of the combustion process.

An increase in weight of the fractional composition of the fuel
leads to an increase in carbon formation (Table 16).

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Table 16. Influence of the fractional composition of fuel on carbon formation.

Fuel	Temperature of boiling out 10% of the fuel, °C	Carbon deposit, ℓ
Aviation gasoline......	62	0.19
Aviation kerosene.......	173	0.83
Diesel...........	238	0.89

An increase in the aromatic and unsaturated hydrocarbons in the fuel composition also leads to an increase in carbon formation (Table 17).

Table 17. Carbon-deposit forming capability of individual hydrocarbons and fuels.

Fuel	Temperature of the beginning of boiling, °C	C:H ratio	Carbon deposit, ℓ	Fuel	Temperature of the beginning of boiling, °C	C:H ratio	Carbon deposit, ℓ
Isodecane..........	201	5.6	0.40	Toluene.........	100	10.5	1.15
Cyclohexane........	80	6.0	0.45	Benzene.........	80	12.0	1.64
Aviation kerosene........	173*	6.2	0.83	Methylnaphthalene	243	13.2	2.79

*10% boiling out temperature.

As evident from the table, the aromatic hydrocarbons having the highest ratio of carbon to hydrogen have the greatest tendency to carbon formation, less - naphthenic, and the least - paraffins.

On the basis of experimental studies empirical equation was developed which connects the tendency to carbon formation of fuels to the ratio of C:H and the 10% boiling out temperature (for individual hydrocarbons - with their boiling temperature):

$$W = \frac{\ln\left(\frac{C}{H}k_1 - k_2\right)}{k_3} + \frac{t}{k_4} - k_5,$$

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where k_1, k_2, k_3, k_4, k_5 - coefficients depending on the conditions of combustion; t - the temperature of boiling out 10% of the fuel, °C; $\frac{C}{H}$ - ratio of the number of carbon atoms to the number of hydrogen atoms.

For an experimental chamber this empirical equation with number coefficients takes the following form:

$$W = \frac{\ln\left(\frac{C}{H}0{,}83 - 1{,}5\right)}{0{,}54} + \frac{t}{225} - 3{,}0.$$

Similar empirical equations cannot be used for calculating carbon formation in all cases, but are suitable for a comparative evaluation of the influence of the fuel composition on carbon formation. Fuels possessing a large density have greater carbon-deposit forming capacity because with an increase in density, as a rule, the 10% boiling out temperature of the fuel increase (Fig. 54).
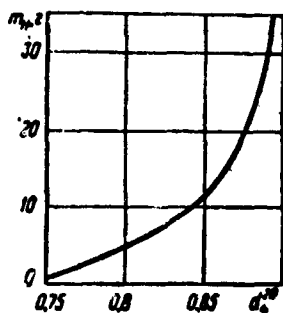
Fig. 54. Dependence of the deposit of carbon (m_H) in the combustion chamber of a jet engine on the density of the fuel.

The content of resinous substances, sulfur, and other impurities in the fuel increases carbon formation in the engine.

Increased carbon formation in a gas-turbine engine is harmful and dangeous for the following reasons:

Increased carbon formation on the walls of the combustion chamber impairs the thermal conductivity and can cause local overheatings and warping of the metal of the chamber;

increased carbon formation can lead to clogging with cove of openings in the heat tube through wh ch secondary air enters the chamber which can change the character of the movement of gases in the combustion chamber and can have an effect on the process of combustion;

formation of a carbon deposit on the injectors can cut off the fuel supply to the combustion chamber;

pieces of the carbon deposit that separate from the walls of the combustion chamber and are taken away by the gas flow cause erosion of the blades of the gas turbine engine.

CHAPTER IV

GRADES OF FUELS FOR AVIATION JET ENGINES

1. Native Fuels

Today the basic fuels for the jet engines of civil transport aircraft are the kerosenes T-1, TS-1, T-7, T-6, T-2.

The T-1 fuel is a product of the direct distillation of low-sulfur oil, the boiling out temperature limits — 150-280°C.

The TS-1 — a product of the direct distillation of sulfurous oil, the boiling out temperature limits — 150-250°C.

The T-1 and TS-1 fuels are the most widespread in civil aviation. Their deficiency is a relatively low stability at elevated temperatures.

A native oil-refining industry produces the thermostable fuels T-7 and T-6.

The fuel T-7 is a product of the direct distillation of sulfurous oil subjected to hydrodesulfurization. The temperature limits of boiling out are 150-250°C. The T-7 fuel can be used both in the pure form, and with antiwear additives. The T-6 fuel is a product of the direct distillation of oil. The temperature limits of boiling out are 195-315°C.

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Grade T-2 kerosene is a wide fraction fuel with temperature limits of boiling out 60-280°C, it is obtained by the direct distillation of sulfurous oil.

The technical conditions for native grades of fuels for jet engines are given in Table 18, some of their physicochemical characteristics not normalized by a standard, — in Table 19.

Table 18. Technical conditions for the fuels T-1, TS-1, T-2, T-6, T-7.

Indicator	According to GOST 10227-62			According to GOST 12308-66	
	T-1	TS-1	T-2	T-6	T-7
Density at 20°C, g/cm^3, not less than	0.800	0.775	0.755	0.840	0.775
Factional composition: temperature of the beginning of distillation, °C:					
not higher than.............	150	150	—	—	150
not lower than.............	—	—	.60	195	—
10% is distilled at a temperature, °C, not higher than........................	175	165	145	220	165
50% is distilled at a temperature, °C, not hi her than........................	225	195	195	255	195
90% is distilled at a temperature, °C, not higher than......................,......	270	230	250	290	230
98% is distilled at a temperature, °C, not higher than......................:......	280	250	280	315	250
Viscosity kinematic, cSt: at a temperature of 20°C:					
not more than...............	—	—	—	4.5	—
not less than...............	1.50	1.25	1.05	—	1.25
at a temperature of -40°C, not more than...............	16	8	6	60	8.0
Lowest heat of combustion, Kcal/kg, not less than......	10 250	10 250	10 300	10 300	10 300
Height of a sootless flame, mm, not less than..........	20	25	25	20	25

Table 18. Continuation

Indicator	According to GOST 10227-62			According to GOST 12308-66	
	T-1	TS-1	T-2	T-6	T-7
Acidity, mg KOH per 100 ml of fuel, not more than......	0.7	0.7	0.7	0.5	0.5
Pressure of the saturated vapors, mm Hg., not more than......................	—	—	100	—	—
Flash temperature in a closed crucible, °C, not lower than.................	30	28	—	—	28
Temperature of the beginning of crystallization, °C, not higher than.................	-60	-60	-60	-60	-60
Iodine number, g of iodine per 100 g of fuel, not more than......................	2	3.5	3.5	1.0	0.5
Content of aromatic hydrocarbons, %, not more than..	20	22	22	10	22
Thermal stability at 150°C for 4 h, mg per 100 ml of fuel, not more than........	18	10	10	—	—
Thermal stability under static conditions at 150°C for 5 h: amount of insoluble deposit, ml per 100 ml of fuel, not more than........	—	—	—	6.0	6.0
amount of resins, insoluble in the fuel.................	Absent				
amount of resins, soluble in the fuel................	Not standardized, determination required				
Content of actual resins, mg per 100 ml of fuel, not more than...................	6	5	5	6	4
General content of sulfur, %, not more than...........	0.1	0.25	0.25	0.05	0.05
Mercaptan sulfur content, %, not more than...........	—	0.005	0.005	Absent	0.001
Hydrogen sulfide content...	Absent				
Test on a copper plate at 100°C for 3 h..............	With stands without changing the color of the plate				
Content of water-soluble acids and alkalis.........	Absent				
Ash content, %, not more than......................	0.003	0.003	0.003	0.003	0.003
Content of foreign impurities and water.......	Absent				
Final filtration, l/min, not less than..............	0.1	—	—	—	—

Table 19. Physicochemical characteristics of native fuels, not normalized by a standard.

Indicator	T-1	T-1	T-2
Temperature of correction of density at $1°C$	$75 \cdot 10^{-5}$	$80 \cdot 10^{-5}$	$83 \cdot 10^{-5}$
Coefficient of volumetric expansion	$94 \cdot 10^{-5}$	$98 \cdot 10^{-5}$	$100 \cdot 10^{-5}$
Heat capacity at $20°C$ average, kcal/kg.	0.47	0.48	0.50
Surface tension at $20°C$, dyn/cm	26	25	23
Heat of vaporization average, kcal/kgf.	50	55	60
Elementary chemical composition, %.			
hydrogen	14.0	14.4	14.5
carbon	86.0	85.6	85.5
Group chemical composition, % by volume:			
paraffins	30	60	60
naphthenes	55	25	20
aromatics	15	15	15
unsaturated	1-2	1-2	1-2
Solubility of water in the fuel at $20°C$ average, %	0.005	0.007	0.008
Solubility of the fuel in water at $20°C$, %	0.001	0.001	0.001
Solubility of air in the fuel on the earth at $20°C$, % by volume	12	13	14
Temperature of spontaneous combustion (droplet method) average, $°C$	220	220	230
Temperature limits of explosion-hazard mixtures on the earth, $°C$:			
lower	25	20	-10
upper	65	57	34
Concentration limits of explosion-hazard mixtures on the earth average, % by volume	1.4-7.5	1.2-7.1	1.1-6.8
Limits of pressure of the saturated vapors, at which the formation of explosion-hazard mixtures is possible, mm Hg	8-95	8-95	8-95
Specific electrical conductivity:			
Ω^{-1}	10^{-12}	10^{-12}	10^{-12}
cm^{-1}	10^{-15}	10^{-15}	10^{-15}
Rate of burnout of the fuel from a surface, mm/min	1.3	1.7	1.8
Temperature of a heated surface, at which the fuel in contact with the surface will ignite, $°C$	325	325	330

2. The Interchangeability of Native and Foreign Fuels

Each year USSR civil aviation opens new international lines. A large number of native aircraft accomplishes flights into foreign airports. Simultaneously a large number of foreign aircraft fly into the Soviet Union. All this leads to necessity to refuel native aircraft with foreign fuels, and foreign aircraft with native fuel.

In solving the problem of the interchangeability of native and foreign fuels it is necessary to be convinced that these fuels are identical according to their physicochemical properties. The fractional composition, low-temperature properties, heat of combustion, corrosive properties, and other characteristics of the fuels (substituting and substituted) should be very close in order not to cause any breakdowns in the operation of the fuel system and power plant of an aircraft.

On the basis of studies of the interchangeability of native and foreign fuels being conducted in the State Scientific Research Institute of Civil Aviation, an appropriate manual issued. This manual is confirmed by the Minister of Civil Aviation and is the basic document followed by crews when servicing aircraft at foreign airports, and also by workers of [GSM] (ГСМ) fuel and lubricants and [ATB] (АТБ) Air Technical Base services, which provide servicing with fuel and lubricating materials and servicing of aircraft, and servicing of the aircraft of foreign airlines in civil aviation airports.

Table 20 gives the grades of fuels which are interchangeable in native and foreign aircraft.

Technical norms for some grades of foreign fuels are given in Tables 21 and 22.

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Table 20. Interchangeability of native and foreign grades of fuels.

Types of aircraft	Fuel	
	Soviet Union	Foreign countries
Tu-104, Tu-124, Tu-134, Il-62.....	TS-1, T-1	Avtur-50, Avtur-650, Tip 1, tip A-1, ATK, ATG, P-5 (avkat), P-1 P-1
"Caravelle," "Comet IV," "Boeing 727," "Boeing-720," "Douglas DC-8," Tu-114,	TS-1, T-1	The same
Il-18, An-10, An-12, An-24,	TS-1, T-1	»
"Viscount"; "Bristol-Britania 310," "Lockheed Electra-2"	TS-1, T-1	»

Table 21. Technical norms for jet fuels of England, France, and the Czechoslovak Socialist Republic.

Indicators	Specification and technical norms		
	England	France	Czechoslovakia
Specification number	DERD-2494	Air —3405/B	ТРД· 25-005-64
Brand of fuel	Avtur 50	Avtur 50	PL-4
Density at 15°C:			
not less than	0,775	0,775	—
not more than	0,825	—	—
Density at 20°C	—	—	0,775 —0,976
Fractional composition,°C:			
temperature of the beginning of distillation, not higher than . .	—	—	150
10% distilled at a temperature			
not higher than	—	—	165
not lower than	—	204	—
20% distilled at a temperature			
not lower than	200	—	—
50% distilled at a temperature			
not higher than	—	—	195
not lower than	—	232,2	—
90% distilled at a temperature			
not higher than	—	—	230
98% distilled at a temperature			
not higher than	—	—	260
Temperature of the end of boiling·	300	288	—
Viscosity kinematic, cSt:			
at 20° . not less than	—	—	1,25
» —18°C, not more than . . .	6,6	16,0	—
» —34,4°C, » »	—	—	—
» —40°C, » »	—	—	8,0
Flash temperature, °C:			
not lower than	37,8	38	25
not higher than	—	66	—

Designation: ТРД = TRD = Turbojet Engine.

Table 21. (Cont'd).

Indicators	Specification and technical norms		
	England	France	Czechoslovakia
Temperature of the beginning of crystallization, °C not higher than.	−50	−50	−60
Bromine number, g of bromine per 100 g of fuel, not more than, . . .	5	—	—
Iodine number, g of iodine per 100 g of fuel, not more than. . . .	—	—	3,5
Content of aromatic hydrocarbons, % by volume, not more than.	20	20	22
Content of actual resins, mg per 100 ml, not more than	7	7	5
General sulfur content, %, not more than.	0,2	0,2	0,1
Content of mercaptan sulfur %, not more than	0,001	0,001	0,001
Corrosion of a copper plate . . .	Absent	—	—
Acidity:			
mg KOH/g not more than	—	0,1	—
mg KOH/ml not more than	—	—	0,7
Height of a sootless flame (smudging point), mm, not less than	20	25	—
Heat of combustion lowest, kcal/mg, not less than	—	10 200	10 250

Table 22. Technical norms for jet fuels of Canada, USA, and Japan.

Indicators	Specifications and technical norms		
	Canada	USA	Japan
Specification number	3GP-23e	D1655/63 т	DERD-2496
Brand of fuel	Tip 1	Tip A-1	IP-5
Density at 15°C:			
not less than	—	0,775	0,788
not more than	—	0,830	0,845
Fractional composition:			
10% of the fuel is distilled at a temperature, °C, not higher than. . .	—	204	204
20% of the fuel is distilled at a temperature, °C, not higher than . .	200	—	—
50% of the fuel is distilled at a temperature, °C, not higher than . .	—	232.2	—
Temperature of the end of boiling, °C. .	300	288	288
Viscosity kinematic, cSt, not more than:			
at −34° C	—	15	16,5
» −40° C	15	--	—
Flash temperature, °C, not lower than .	39,4	40,3—	60
Temperature of the beginning of crystallization, °C, not higher than . .	−48	−50	−48
Bromine number, g of bromine/100 g, not more than	—	—	5
Content of aromatic hydrocarbons, % by volume, not more than .	22	20	25
Content of actual resins, mg/100 ml of fuel, not more than . .	7	7	7
Content of potential resins, ml/100 ml of fuel, not more than . .	—	—	14

Table 22. (Cont'd).

Indicators	Specifications and technical norms		
	Canada	USA	Japan
General sulfur content, %, not more than	0.2	0.3	0.4
The same, mercaptan sulfur, %, not more than	0.001	0.003	0.001
Corrosion of a copper plate	—	—	Отсутст
Acidity, mg KOH/g, not more than	—	0.1	—
Point of smudging, mm, not lower than	20	20	19
Heat of combustion lower, kcal/kg, not lower than	—	—	10 170
Thermal stability:			
drop in pressure after 5 h, inches Hg, not more than	—	12	13
deposits, g, not more than	—	3	3

3.   Promising Fuels for Jet Engines

Jet aviation today is satisfied basically with kerosene type
fuels. The further development of aviation and primarily the increase
in speed, distance, and flight altitudes requires the creation of
higher-quality fuels. Most important is the creation of fuels which
possess considerably higher energy indexes than the kerosenes. The
following refer to energy indexes: the heat of combustion, density,
and the combustion efficiency. Intensive research works are being
accomplished in t'is direction. The basic paths in solving this
problem are the following:

improvement of the energy characteristics of petroleum fuels
by means of the appropriate selection of the method for technological
processing of raw material;

creation of synthetic fuels;

use of metals as fuels or components of fuels;

use of free radicals as fuels;

use of the energy of nuclear processes.

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The investigations conducted on the study of the energy characteristics of petroleum fuels, the separate classes of hydrocarbons, and the various fractions made it possible to establish that which under the most favorable conditions it is possible to obtain a fuel whose energy characteristics will be higher than the better types of kerosene by not more than 5-7%. The most promising in this respect are paraffin-naphthene hydrocarbons, whic boil away at a temperature of 300-350°C and above. Thus, this path obtaining highly effective fuels does not completely solve the problem.

A more promising and effective method for obtaining fuels with high energy characteristics is the creation of synthetic fuels. By means of the synthesis of hydrocarbons it is possible to get fuels with energy characteristics 13-15% better than those of kerosene. Today fuels are known which are based on isoparaffin hydrocarbons with the compact location of lateral groups, several naphthenic hydrocarbons with lateral chains based on bi- and polycyclic naphthenic hydrocarbons. The characteristic positive feature of these fuels is also the high thermal stability at temperatures up to 260°C, and their deficiency — high viscosity at negative temperatures.

Obtaining highly effective fuels by means of the synthesis of hydrocarbons is associated with severe difficulties because besides hydrogen possessing a high heat of combustion (28,700 kcal/kg) carbon, which possesses a low heat of combustion (7800 kcal/kg), enters the molecule of hydrocarbon. At the same time a number of elements whose heat of combustion is significantly higher than that of carbon is known. Thus, by replacing carbon with a high-calorie element it is possible to obtain fuel with very good energy characteristics. Thus, for instance, boron has a calorific value 78% higher than that of carbon. With a content of much the same weight fraction of hydrogen as also in hydrocarbons, hydroborides during combustion give 50-60% more heat.

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At this time intensive research works on obtaining fuels based on synthetic compounds of hydrogen with elements possessing a high heat of combustion are being carried out. As an example it is possible to examine fuels based on hydroborides as the most mastered.

Pure boron — a solid substance of a black color that melt at a temperature of 2300°C, boil at 2550°C and ignite in air upon heating at 800°C. Crystalline boron has a density of 3.33, amorphous — 2.30-2.34. Studies showed that the greatest practical interest as a basis of obtaining boron fuels is in the stable compounds of boron with hydrogen: pentaborane and a decaborane and their alkyl derivatives.

Pentaborane (B_5H_9) — a light liquid, density 0.61-0.63, boiling point +58°C and freezing point -47°C. At ordinary temperatures decomposition of pentaborane practically does not occur, at 150°C it speeds up noticeably, and at 300°C it goes rapidly. Decomposition is accelerate during interaction with water. Mixtures of the vapors of pentaborane with air are explosive and sometimes they self-ignite. In connection with this it must be hermetically sealed during storage. Pentaborane is extremely poisonous, causing the destruction of the central nervous system. The heat of combustion of pentaborane during the formation of solid boric anhydride — 16,200 kcal/kg, of liquid 15,340 kcal/kg. In an engine those temperature conditions at which boric anhydride is formed in the liquid state are the most probable. In this case its heat of combustion is 50% higher than the heat of combustion of kerosene. However in view of the low density of pentaborane its volumetric heat of combustion is not considerably more than that of kerosene.

Pentaborane dissolves well in hydrocarbons. This makes it possible to use it in a mixture with hydrocarbon fuels. The positive features of pentaborane are the high rate of burning (several times higher than that of kerosene) and the stability of the flame which is especially important for direct-flow engines.

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Decaborane ($B_{10}H_{14}$) -- a solid substance, density — 0.92, melting point — 99°C, boiling — 213°C. In the solid form it is completely stable, noticeable spontaneous decomposition of it begins at a temperature of 170°C. Solid decaborane does not react with oxygen at an ordinary temperature, but the liquid self-ignites in air at a temperature of 100°C. The heat of combustion of decaborane (during the formation of liquid boric anhydride) equals 15,310 kcal/kg, its volumetric heat of combustion in view of the greater density is approximately 1.5 times higher than that of pentaborane, and 65-70% higher than that of kerosene. As a result of its low volatility decaborane is considerably less dangerous in handling than pentaborane.

Today studies are being conducted on obtaining and using alkylated borane — products of the substitution of separate atoms of hydrogen in pentaborane and decaborane for hydrocarbon radicals. Although alkyl boranes possess a lower heat of combustion, they are however more stable and less poisonous than nonalkylated hydroborides.

A study of the thermal stability of liquid boranes at various temperatures showed that they decompose rapidly with the formation of gaseous products and insoluble deposits. The gaseous products of decomposition facilitate the formation of a vapor lock in the fuel system, and the deposits clog fuel filters. The use of boron fuels in gas-turbine engines is still difficult because during combustion they produce solid deposits of boric oxide on the combustion chamber walls and on the turbine blades.

The basic advantage of fuels based on boranes in comparison with kerosene — the high energy characteristics which make it possible to increase the flight range of an aircraft by approximately 40%. Furthermore, the high chemical activity of boranes in reaction with air can provide for a greater altitude of an aircraft with jet engines than can kerosene because borane-air mixtures burn at such low pressures while kerosene does not burn.

Metalorganic fuels relate to promising synthetic fuels. Today fuels based on triethyl aluminum, triethyl boron, trimethyl aluminum, and others are known. Metalorganic fuels in their energy character- istics differ little in practice from the kerosene-type hydrocarbon fuels. The major advantage of these fuels in comparison with kerosene is their considerably more stable combustion at low pressures in the combustion chamber. This increases the altitude of an aircraft.

A method of obtaining promising fuels with a high heat of combustion and fuels during the burning of which a considerable increase occurs in the burning zone temperature can be the use of metals as components of petroleum or synthetic fuels. One of the methods of obtaining such fuels is the creation of suspensions or colloidal solutions of metals in hydrocarbon media. To obtain colloidal solutions in a hydrocarbon medium solid particles 10^{-5}-10^{-7} cm in size should be dispersed.

Obtaining colloidal solutions of a high concentration is a difficult task. It is easier to get suspensions of powder-like metals in a hydrocarbon medium. In this instance to create stable suspensions it is necessary to avoid precipitation of the dispersed particles. For the characteristics of stability of real suspensions of metals in a hydrocarbon medium with a certain approximation, it is possible to use Stokes' law, according to which

$$v = \frac{2}{9} g \frac{r^3 (D-\rho)}{\eta}.$$

where v — the rate of precipitation of the particles, cm/s; g — the acceleration of free fall, cm/s^2; r — the radius of the solid particles, cm; ρ — the density of the liquid medium, g/cm^3; η — the dynamic viscosity of the liquid medium, g/(cm·s); D — the density of the solid particles, g/cm^3.

From the Stokes equation it follows, that it is possible to increase the stability (to decrease the rate of precipitation) of

suspensions due to the following factors: an increase in the viscosity
of the medium η; a decrease in the particles of the dispersed
substance; a decrease in the difference between the density of the
liquid medium and the density of the dispersed substance.

To increase the viscosity thickening additives are introduced into
metal-hydrocarbon fuels — rubber, polyisobutylene, wax, petrolatum,
aluminum, sodium, and other salts of high-molecular organic acids.

Good results are given by surface-active additive, added into
the hydrocarbon medium. In this instance the surface-active molecules
of the additive are absorbed on the surface of the solid particles
and they seemingly increase the resistance during movement of the
solid particles.

Today beryllium, aluminum, magnesium, lithium, boron, and others
have been studied as components of metal-fuel suspensions.

The use of metal-fuel suspensions gives the possiblity to
considerably increase the thrust of an engine and the flight speed.
Thus, for example, fuel consisting of 50% magnesium powder and 50%
octane can provide up to 50% greater thrust of an engine, than
kerosene. Figure 55 gives the temperatures of the combustion of
metallic fuels and their suspensions in hydrocarbon fuel. Another
advantage of the metals is their high volumetric heat of combustion,
exceeding in certain cases by 2-3 times the volumetric heat of
combustion of kerosene. This makes it possible to considerably
increase the flight range of an aircraft. The heat of the combustion
of some metallic fuels is given in Table 23.
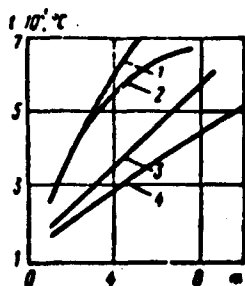
Fig. 55. Temperature of combustion of metallic fuels
and their suspensions in hydrocarbon fuel: 1 —
magnesium; 2 — aluminum; 3 — 50% magnesium +50%
kerosene; 4 — kerosene.

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Table 23. Heat of combustion of metallic fuels.

Fuels	Relative density at 20°C	Heat of combustion by weight (highest), kcal/kg	Volumetric heat of combustion (highest), kcal/kg	Comparison with kerosene (the data for kerosene accepted as 1)	
				Volumetric heat of combustion	Volume of the tanks with an identical reserve of heat energy
Pure powders:					
beryllium	1,82	15 000	27 300	3,25	0,31
boron	2,3	13 950	32 100	3,81	0,26
aluminum	2,7	7 290	19 700	2,35	0,42
magnesium	1,74	6 000	10 450	1,25	0,82
Mixture 50% powder and 50% kerosene (by weight):					
beryllium	1,13	12 620	14 250	1,70	0,59
boron	1,21	12 100	14 650	1,75	0,57
aluminum	1,26	8 770	11 050	1,32	0,56
magnesium	1,11	8 120	9 000	1,07	0,93

Note: 1. The calorific value of kerosene is accepted a. 10,250 kcal/kg, the density as 0.82.

2. The calorific value is given from the calculation of the formation of the solid oxides of the metals.

Along with improving fuels, with the use of which energy is liberated as a result of oxidation (combustion), researchers in a number of countries are concerned with the problem of using qualitatively new sources of energy for aviation engines. Specifically, works are being conducted on the use of the energy of free radicals. Free radicals are called splinters of molecules — groups of atoms or separate atoms which possess a free valence. It is known, that the dissociation (decay) of molecules into free radicals occurs, as a rule, with a considerable absorption of energy from the outside. Upon association (joining) of the free radicals into molecules this energy is liberated. For example, for dissociation of 1 kg of molecular hydrogen into atoms $H_2 \to H + H$ it is necessary to use 51,300 kcal; in joining the hydrogen atoms into molecules (association) this energy is liberated.

The heat of association of some radicals into molecules is as follows:

$$O + O \rightarrow O_2 + 3640 \ \text{kcal/kg};$$
$$N + N \rightarrow N_2 + 6050 \ \text{kcal/kg};$$
$$F + F \rightarrow F_2 + 1710 \ \text{kcal/kg};$$
$$CH_3 + CH_3 \rightarrow C_2H_6 + 14000 \ \text{kcal/kg};$$
$$C_2H_5 + C_2H_5 \rightarrow C_4H_{10} + 12000 \ \text{kcal/kg};$$
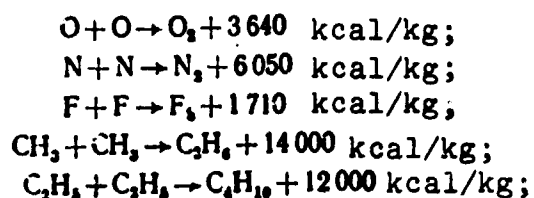
The combustible elements (hydrogen, hydrocarbon radicals), besides liberating heat during association, can react with an oxidizer, as a result of which the heat of association is added to the heat of combustion.

The greatest difficulties when using of this type of energy consist of the fact that free radicals possess a very large chemical activity and under ordinary conditions exist for millionths or thousandths fractions of a second. Therefore, the solution to this problem is connected with the development of methods for conserving free radicals in a free state until they are supplied to the engine. In principle it is possible to conserve the radicals in a free state at very low temperatures (close to absolute zero), very low pressures, and also in a mixture with substances which slow the movement of the free radicals.

A number of scientists point to the principle possibility of using the energy of free atoms of nitrogen and oxygen, which are contained in the atomsphere at high altitudes. Free atoms of nitrogen and oxygen are formed under the influence of ultraviolet rays from the sun at an altitude of 80-100 km. At the very low pressure at such an altitude (0.01 mm Hg and below) the free atoms are preserved for a long period of time. Therefore, in the presence of equipment, in which it would be possible to force the molecules of nitrogen and of oxygen to associate inside of an engine, an aircraft brought to an altitude of 80-100 km would have a practically inexhaustible reserve of energy.

The most powerful source of energy is atomic energy, which today is successfully used in the power plants of ocean going vessels

and in atomic power stations. The use of nuclear energy in aviation engines, in the first place the atomic energy from the splitting of of uranium and plutonium, is considered a matter for future years. The advantages of atomic energy are colossal. It is sufficient to say that one gram of uranium-235 contains approximately as much energy, as two tons of kerosene. An aircraft weighing 100-150 t, to ʼ ʼ ng at a speed of 2000 km/h around the earth, would use a total of 0.5 kg of uranium-235.

The source of heat of all modern atomic energy devices is the nuclear reactor — a device, in which a self-supporting controlled nuclear reaction is taking place. Nuclear fuel uranium is used in the form of rods called heat-emitting elements. That part of the reactor, in which uranium is placed and where the splitting reaction takes place is called the active zone. Around it there is usually a neutron reflector. The purpose of the reflector is to return to the active zone of the reactor the greatest possible number of neutrons emitted from it. Light metals, carbon (in the form of graphite), ordinary and heavy hydrogen are used as reflectors. A reactor should have reliable shielding so that the radiation liberated in the active zone does not penetrate beyond the limits of the reactors.

The heat liberated in a reactor is led away by a heat-carrier which can be various substances depending on the designation and thermal stress of the reactor. Specifically, water under high pressure; the molten metals: sodium, potassium, lead, bismuth, and also gases: helium, nitrogen, and carbon dioxide gas can be used.

An atomic turbojet engine is the simplest of the atomic aircraft engines that are completely self-contained. A very simple diagram of it is shown in Fig. 56 and it operates in the following manner. Air from a compressor enters the reactor located between the compressor and a turbine. Part of the energy of the heated air works in the turbine, which rotates the compressor. Another part in the jet nozzle is converted into kinetic energy issuing from the engine as a jet of

air. Today various diagrams of atomic power plants have been developed.
However wide use of atomic energy in aircraft power plants has run
into severe difficulties.
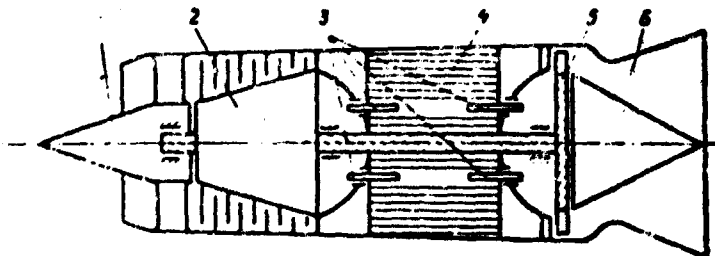
Fig. 56. Line diagram of an atomic turbojet
engine: 1 - inlet cone; 2 - compressor;
3 - control rods; 4 - reactor; 5 -
turbine; 6 - jet nozzle.

CHAPTER V

FUELS FOR PISTON AIRCRAFT ENGINES

1. Peculiarities of the Combustion Process in a Piston Engine

All modern aircraft piston engines are four-stroke with spark ignition. There exist two types of engines with spark ignition: with interior carburetion (direct injection engines) and with external carburetion (carburetor engines).

The suction and compression cycles (about 0.02 s) are used for fuel evaporation in piston engines. To provide for complete evaporation of the fuel in such a short period of time aircraft piston engines require easily vaporized fuel-gasoline.

After ignition of the combustible mixture the flame extends throughout the combustion chamber in the form of a front for 0.002 to 0.003 s. The incandescent products of combustion, expanding, sharply squeeze and strongly heat the still not burned mixture in front of the flame front. As a result of this rapid oxidation of the hydrocarbons takes place in it and easily detonated hydroperoxides are formed. If before the end of combustion mixtures of peroxide are not formed and explode, then the engine will operate normally, but if an explosion of the peroxides leads the normal combustion front

then shock waves will appear in the cylinder — knock occurs. It causes overheating and gradual failure of the parts of the cylinder-piston group. A characteristic sign of knock — the metallic clatter caused by the shock waves.

More or less prolonged operation of the engine in a distinctly expressed knocking condition leads to the failure of its parts: in the first place the piston, sparkplugs, valves.

The appearance and intensity of knocking in piston gasoline engines is determined by the rate of the chemical reactions of the preflame oxidation of the hydrocarbons and by the time during which these reactions can take place. The rate of the chemical reactions of preflame oxidation depends on the chemical composition of the fuel, on the composition of the combustible mixture (α), and also on the pressure and temperature. The temperature and pressure of the mixture in the engine cylinder depend on the temperature and pressure of the air at the inlet, the degree of compression, the temperature of the combustion chamber walls, the piston, and the valves, and also the degree of swirling of the air in the cylinder, which determines the amount of heat transfer to the walls. The appearance of knock combustion depends on a number of structural factors (sizes and forms of the combustion chamber, the location of the sparkplugs, and others).

Other conditions being equal the chemical nature of fuel and the composition of the mixture determine the tendency of the combustible mixture to knock. It has been established from experiences that some hydrocarbons possess higher detonation properties in rich mixtures, others — in lean. Some hydrocarbons detonate more easily in engines with an increase in the degree of compression, others — with an increase in pressurization, and the third — with an increase in the air temperature at the inlet.

With the change in the coefficient of excess air in the
combustible mixture the tendency to knock in all fuels changes. Under
determined conditions of an experiment each fuel has its knock property
and completely determined value α, at which its tendency knock reaches
a maximum.

The knock properties of fuels according to the composition of
the mixture have a large value for the operation of engines since
to decrease the heat strain of parts under forced conditions the
engines operate on rich mixtures (α = 0.6-0.7), and under cruising
conditions to provide the greatest economy — on relatively lean
mixtures (α = 0.9-0.95). The fuel should provide knockless operation
of the engine under all conditions.

Figure 57 shows the knock properties of fuel — the dependence
of the permissible pressurization $P_к$ (corresponding to the initial
knock) on the composition of the mixture at different air temperatures.
From the graph it is evident that at an air temperature higher than
70-100°C (this is usually its temperature after compression in the
supercharger) maximum knock resistance (maximum pressurization $p_к$)
is obtained at α = 0.6-0.7 and minimum — at α = 1.0-1.1. This makes
it possible while operating the engine on a rich mixture to establish
a higher pressurization and to obtain greater power from the engine
than during operation on a lean mixture.
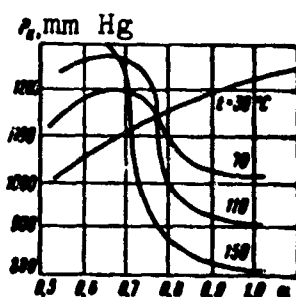
Fig. 57. Dependence of the knock properties of
gasoline on the air temperature at the cylinder
inlet (ASh-82FN engine).

A decrease in the air temperature causes a decrease in the knock
resistance on a rich mixture and an increase on a lean mixture. In

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this case the knock resistance of various gasolines with the change
in the composition of the mixture and the temperature conditions
changes differently. In connection with this the requirements for
knock resistance in gasoline on a rich mixture and on a lean mixture
should be different.

The basic physicochemical properties of fuels, including gasolines,
and the effect of these properties on the operation of the fuel
system of an aircraft and an engine were comprehensively examined in
Chapter III. However considering the peculiarities of combustion
of gasolines in piston aircraft engines, combined with possibility
of knock combustion, it follows to examine more comprehensively the
antiknock properties of gasolines.

2. The Evaluation of the Knock Resistance of Gasolines

Today evaluation of the knock resistance of gasolines is based
on the principle of comparing them with standard fuels in testing
these and those on special one-cylinder devices under strictly defined
standard conditions. Two types of devices are used: a device with
a variable degree of compression (engine, temperature, research) and
a device with a variable degree of pressurization (aviation method
with pressurization).

Table 24 gives the basic parameters of the devices for
determining the knock resistance of aviation gasolines.

Engine method. The essence of determining the knock resistance
of gasolines according to the engine method consists of the fact
that during the operation of a special one-cylinder engine (IT-9-2)
on the tested fuel the standard intensity of knock is established.
Then such a standard fuel is selected, which at a given degree of
compression and mixture composition corresponding to the maximum
intensity of knock, gives the same standard intensity of knock, as

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does the experimental fuel. A mixture of isooctane (2,2,4-trimethyl pentane) and n-heptane is used as the standard fuel. The knock resistance of isooctane (low-knock fuel) is taken as 100, the knock resistance of heptane (easily knocking fuel) – as zero. The evaluation of the knock resistance of the tested fuel is accomplished according to the so-called octane number.

Table 24. Basic parameters of devices for determining the knock resistance of gasolines.

Parameters	Method		
	Engine (GOST 511-61)	Temperature (GOST 3337-52)	Aviation with pressurization (GOST 3338-61)
Engine.................... Number of r/min,.........	IT-9-2 900	IT-9-5 1200	IT-9-1 1800
Temperature of the cooling liquid, °C.....	100	190,5	190,5
Temperature of the air, being sucked in, °C....	25—50	52	107
Temperature of the working mixture, °C....	150	105	Not controlled
Temperature of the oil in the crankcase, °C...	50—70	50—70	75—80
Degree of compression...	Variable 4—10	Variable 4—10	Constant 7
Method of measuring the knock...................	Electromech-cal sensor	Thermocouple	By ear or by a detonation meter
Method of changing the knock intensity........	By a change in the degree of compression		By a change in the pressuriza-tion
Unit of evaluation of knock resistance.......	Octane number	Octane number	Grade
Correspondence of the results of the evalua-tion to the composition of the working mixture. Standard fuels..........	With lean mixtures Mixtures of isooctane and n-heptane	With lean mixtures n-heptane, isooctane and its mixtures with tetra-ethyl lead	With rich mixtures Isooctane and its mixtures with tetraethyl lead

The octane number of gasoline is called the percent (by volume) content of isooctane in a mixture with normal heptane, equivalent in its knock resistance (under standard test conditions) to the tested fuel. Thus, for instance, if the octane number of gasoline is 70, then this means, that the fuel detonates in the same way as a mixture of 70% isooctane and 30% heptane.

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The temperature method. To determine the knock resistance of high-octane aviation gasoline the temperature method is used. Unlike the engine method the measure of the intensity of knock in the temperature method is accepted as the increase in the temperature of the cylinder head and not the size of the pulse of pressure. Evaluation of the intensity of knock of the fuel according to the increase in the intensity of knock of the fuel according to the increase in the temperature of the cylinder head makes it possible to compare and in this way to determine the knock properties of higher-octane fuels than by testing according to the engine method.

The evaluation of the knock resistance of fuels less resistant to knock than isooctane, is expressed in octane numbers, and for the fuels more resistant to knock than isooctane — in numbers of an arbitrary octane number. The arbitrary octane number is determined according to a special graph (Fig. 58).
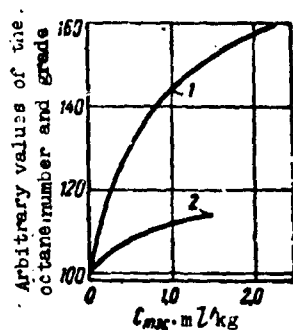
Fig. 58. Dependence of the grade and the arbitrary octane number on the concentration of tetraethyl lead in isooctane: 1 — grade; 2 — arbitrary octane number.

The aviation method. Testing of fuels by this method is accomplished on special standard one-cylinder IT-9-1 engines with a constant degree of compression $\varepsilon = 7$. The knock condition of the device is attained by changing the pressurization of the engine. The intensity of knock is established by special instruments, which catch the vibrations of the cylinder walls characteristic for knock.

The knock property of a fuel is removed by this method. It is represented in the form of the dependence of the mean indicator pressure P_i which corresponds to the operation of an engine at

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standard knock intensity, on the size of ratio G_T/G_B, characterizing the composition of the mixture (Fig. 59). Evaluation of the knock resistance of a fuel according to this method is accomplished by comparing the knock properties of the tested fuel with similar characteristics of the standard fuels, which are isooctane and its mixtures with tetraethyl lead. The knock property of the tested fuel is plotted on a standard grid.
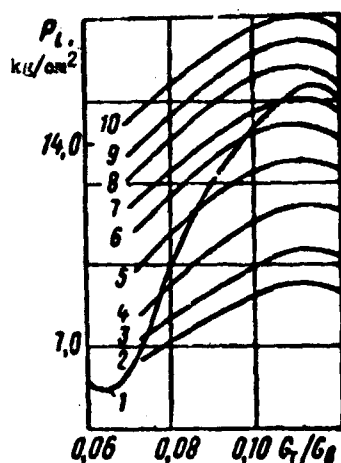
Fig. 59. Comparison of the knock resistance of gasoline with the knock resistance of standard fuels: 1 — gasoline; 2 — pure isooctane; 3 to 10 — mixtures of isooctane with tetraethyl lead.

Comparison and determination of a standard fuel, equivalent in knock resistance to the tested fuel is accomplished with the composition of the mixture G_T/G_B = 0.112, that corresponds to the maximum value P_i for standard fuels.

The size of the grade for standard fuels is established by an experimental method in testing them on one-cylinder devices with various cylinders of series aircraft engines. During these tests on every standard fuel the method of increasing pressurization of the engines led to the appearance of knock and the power was measured which in essence was the maximum possible for each standard. The power obtained during operation on pure standard isooctane was accepted as 100%; mixtures of isooctane with tetraethyl lead made it possible to remove great power moreover with an increase in the concentration of tetraethyl lead size of the maximum possible power also increased. It was established that pure isooctane has a grade

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of 100, isooctane with a concentration of tetraethyl lead of 0.76 ml/kg has a grade of 130, etc., (see Fig. 54).

Thus, the grade of fuel shows how much more or less power can be obtained from a special one-cylinder engine on a rich mixture of the tested fuel in comparison with power developed by this engine on isooctane.

For example, grade 130 shows that this fuel during the operation of a special one-cylinder engine provides an increase of power of 30% in comparison with pure isooctane. The higher the grade of fuel, the better its knock resistance on rich mixtures under conditions of pressurization.

3. The Knock Properties of Hydrocarbons

The knock resistance of hydrocarbons depends mainly upon their chemical nature. The structure of the hydrocarbon components of fuel most strongly influences their knock resistance.

Liquid paraffin hydrocarbons of a normal structure possess the least knock resistance; in this case with an increase in the molecular weight their knock properties deteriorate. The octane numbers determined according to the engine method, have the following values for paraffin hydrocarbons:

octane	17	pentane	61
heptane	0		
hexane	26	butane	92

The knock resistance of isoparaffin hydrocarbons is significantly higher than the knock resistance of similar hydrocarbons of a normal structure and changes depending on the degree of branching and the character of location of the lateral radicals. The values of octane numbers determined according to the engine method for isoparaffin hydrocarbons are the following:

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n-hexane.................................................    0
2-methylhexane............................................   45
3-methylhexane............................................   65
2,4-dimethyl pentane......................................   82
2,3-dimethyl pentane......................................   89
2,3-dimethyl pentane......................................   93
2-methylpropane (isobutane)...............................   99
2,2,4-trimethyl pentane (isooctane).......................  100
2,2,3-trimethyl butane....................................  101
```

The cyclic structure of the molecules of hydrocarbons also increases their knock resistance. The knock resistance of aromatic hydrocarbons is especially high. Octane numbers for some cyclic hydrocarbons have the following values:

```
cyclohexane...............................................   77
methyl cyclopentane.......................................   82
cyclopentane..............................................   83
ethylbenzene..............................................   98
toluene (methylbenzene)...................................  104
benzene...................................................  108
```

Modern aircraft engines require fuels with a high knock resistance. The octane numbers of even the best grades of gasolines obtained from high-quality oils do not exceed 80 units. In connection with this modern aviation gasolines are mixtures of gasolines of the direct distillation or catalytic cracking process with high-octane components and special antiknock additives.

4. High-Octane and Antiknock Components

The high-octane components of aviation gasolines are the individual hydrocarbons: isopentane, neohexane, isooctane, triptane, benzene, toluene, their mixtures and mixtures of isoparaffin hydrocarbons.

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The change in the octane numbers and grade of the base gasolines depending on their content of high-octane components is shown in Figs. 60 and 61. The presence in aviation gasolines of high-octane components should not change the other physicochemical properties of the fuels which are dictated by the operational requirements (volatility, temperature of crystallization, hygroscopicity, and others). High-octane components can be added to gasolines in quantities up to 40%.
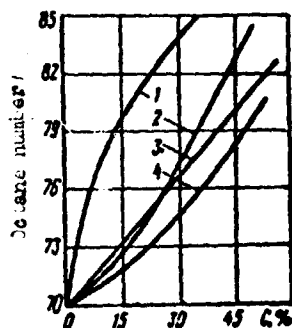
Fig. 60. Dependence of the octane number of aviation gasoline on the concentration of components in it: 1 -- ethanol; 2 -- alkyl benzene; 3 -- isooctane; 4 -- benzene.
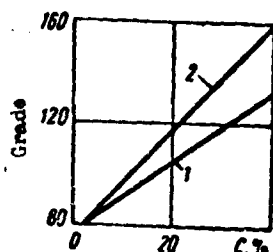
Fig. 61. Dependence of the grade of aviation gasoline on the concentration of components in it: 1 -- benzene; 2 -- alkyl benzene.

Unlike high-octane components antiknock compounds are added to gasolines in always insignificant quantities. They in practice do not change the chemical composition of the fuel.

Today tetraethyl lead $Pb(C_2H_5)_4$ is used as an antiknock compound. Tetraethyl lead is a colorless very poisonous liquid. At a temperature of 20°C its density equals 1.652, at 200°C it boils and simultaneously decomposes. Tetraethyl lead slows down the process of the formation of explosive peroxides.

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The addition of the first small amounts of tetraethyl lead (up to 2.5-3.3 ml/kg is very effective (Fig. 62). A further increase in its content in gasoline increases the knock resistance little but in return negatively influences the reliability of an engine because of the large deposits of lead on the parts of the combustion chamber.
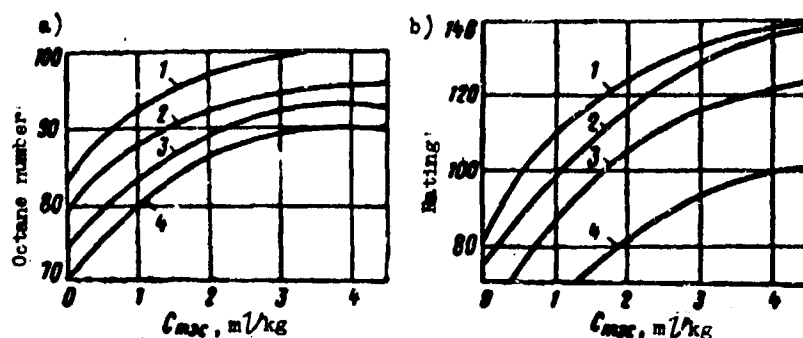
Fig. 62. Dependence of the octane number is lean mixtures (a) and the rating in rich mixtures (b) of basic gasolines on the content of tetraethyl lead in them : 1 — B-100/130; 2 — B-95/130; 3 — B-91/115; 4 — B-70(B-89).

Tetraethyl lead is put into gasoline in the composition of an ethyl liquid in a mixture with "scavengers," with which the metallic lead reacts and the lead oxide after combustion turns into compounds which are volatile at high temperatures and basically are removed from the combustion chamber together with an exhaust gases. Today alkyl halides (C_2H_5Br and $C_2H_4Br_2$) are used as "scavengers." The interaction of the "scavenger" with metallic lead and lead oxide takes place in the following form:

$$2C_2H_5Br \rightarrow 2C_2H_4 + 2HBr;$$
$$Pb + 2HBr \rightarrow PbBr + H_2;$$
$$PbO + 2HBr \rightarrow PbBr_2 + H_2O.$$
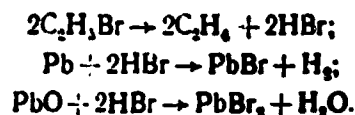
The boiling point of the halide compounds of lead is considerably lower than the temperature in the combustion chamber of an engine, therefore during the combustion of fuel these compounds are found in a vaporous state.

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Three different types of ethyl liquids are added to gasolines:
P-9, 1-TS, and П-2. They differ in the tetraethyl lead content and
in the composition of the "scanenger." Table 25 gives the compositions
of the native liquids P-9, 1-TS, and П-2 and the liquid 1-T which is
used in USA and England.

Table 25. Composition of ethyl liquids.

Components	P-9	1-TS	П-2	1-T
	GOST 988-58			
Tetraethyl lead, %, not less than	54,0	59,0	55,0	61,41
Ethyl bromide, %, not less than..	33,0	—	—	—
Dibromoethane, %, not less than..	—	36,0	—	35,68
Dibromopropane, %, not less than.	--	—	34,6	—
Monochloro naphthalene, %........	6,8±0,5	—	5,5±0,5	—
Dyes, %..........................	0,1	0,5	0,1	0,05
Filler (gasoline)................	—	Remainder to 100%		

During the prolonged storage of gasoline the tetraethyl lead
gradually oxidizes, decomposes, and enters into a reaction with the
products of oxidation of the hydorcarbons. As a result a white
sediment is formed, which can disrupt the normal operation of the fuel
apparatus. The decomposition of tetraethyl lead can also lead to
the appearance of knock in engines. To increase the stability of
tetraethyl lead dissolved in gasoline an antioxidant additive is
added to the gasoline -- paraoxydiphenylamine in the amount of
0.004-0.005%.

5. Brands of Aviation Gasoline

Industry produces the following brands of aviation gasolines:
B-100/130, B-95/130, B-91/115, B-70 (all GOST 1012-54) and BA
(GOST 5760-51), equivalent to the American gasoline 115/145.

Modern gasolines are mixtures of several components. Gasoline
of direct distillation from selected oils and gasolines of catalytic
cracking are used as base gasolines, which are the basic component
part of aviation gasolines. To get the required antiknock properties
isoparaffin and aromatic components are added to the base gasoline.

Aviation gasoline B-100/130 is obtained by mixing gasoline of catalytic cracking with high-quality components. Both gasolines of catalytic cracking, and gasolines of direct distillation serve as base gasolines for B-95/130 and B-95/115. The bases for B-91/115 and B-70 a: gasolines of direct distillation.

Furthermore, aviation gasoline with mixture SB-78 (TU 4-60) is used in civil aviation. This type of gasoline is prepared at the place where required by mixing standard aviation gasolines in the following ratio in percentages by volume: 25% B-91/115 + 75% B-70 or 20% B-95/130 + 80% B-70.

Technical norms for the gasolines used in civil aviation are given in Table 26.

In view of the fact that aviation gasolines are manufactured from oils of various deposits, and also by mixing various high-octane components, the chemical composition and some physicochemical properties of them differ somewhat which is evident from Table 27, where the properties of gasolines are given.

Each gasoline should be used in those engines, for which it is intended (B-95/130 — ASh-82 all modifications; B-91/115 — ASh-62IR and AI-26V, all modifications; SB-78 — AI-14VF, and others, B-70 — AI-14R).

During flights of native aircraft into foreign countries and with the need for servicing the aircraft it is necessary to follow the special instructions of the Ministry of Civil Aviation of the USSR on the interchangeability of native and foreign gasolines. In foreign airports Il-14 aircraft can be refuelled with 100/130 gasolines, An-2 and Li-2 aircraft — with 91/96 gasolines.

Table 26. Technical norms for aviation gasolines.

Indicators	BA	B-100/130	B-95/130	B-91/115	B-70	SB-78
Tetraethyl lead content, g/kg, not more than..................	2,7	2,7	3,3	2,5	0	0,6
Knock rating:						
Octane number according engine method, not less than	—	98,6	95	91	70	78
Octane number according to the temperature method, not less than..........................	—	100	—	—	—	—
Grade in a lean mixture, not less than....................	115	—	—	—	—	—
Grade in a rich mixture, not less than....................	160	130	130	115	—	—
Heat of combustion, lower, kcal/kg, not less than........	10 400	10 300	10 300	10 300	—	10 300
Fractional composition:						
temperature of the beginning of boiling, °C, not lower than...	40	40	40	40	40	40
temperature of 10% boiling out, °C, not higher than...........	75	75	82	82	88	—
temperature of 50% boiling out, °C, not higher than...........	105	105	105	105	105	105
temperature of 90% boiling out, °C, not higher than..........	145	145	145	145	145	145
temperature of 97.5% boiling out, °C, not higher than......	180	180	180	180	180	180
residue and lossess, %, not more than....................	2,5	2,5	2,5	2,5	2,5	2,5
Pressure of saturated vapors, mm Hg:						
not less than..................	240	240	220	220	—	210
not more than..................	360	360	360	360	360	360
Acidity, mg KOH per 100 ml gasoline, not more than...........	1,2	1,0	1,0	1,0	1,0	1,0
Temperature of the beginning of crystallization, °C, not higher than..................	—60	—60	—60	—60	—60	—60
Iodine number, g of iodine per 100 ml of gasoline, not more than....................	6	12	12	10	10	12
Content of actual resins, mg per 100 ml gasoline, not more than....................	2	2	2	2	2	2
Sulfur content, % not more than	0,05	0,05	0,05	0,05	0,05	0,05
Aromatic hydrocarbons content, %, not more than..............	—	—	—	—	20	20
Tests on a copper plate........				Pass		
Content of water-soluble acids and alkalis...................				Absent		
Content of mechanized impurities and water................				Absent		
Transparence....................				Transparent		
Color...........................	Depending on the color of the ethyl liquid	Bright orange	Yellow	Green	Color-less	—

Table 27. Properties of gasoline not standardized.

Indicators	BA	B-95/130	B-91/115	B-76
Density, mean at 20^oC, g/cm^3	0,710	0,730	0,735	0,740
Coefficient of volumetric expansion.	$120 \cdot 10^{-5}$	$110 \cdot 10^{-5}$	$110 \cdot 10^{-5}$	$110 \cdot 10^{-5}$
Temperature correction of density for 1^oC.	$88 \cdot 10^{-5}$	$85 \cdot 10^{-5}$	$85 \cdot 10^{-5}$	$84 \cdot 10^{-5}$
Heat capacity, at 20^oC, kcal/kg...	0,5	0,5	0,5	0,5
Heat of vaporization, mean, kcal/kg.	75	70	70	70
Surface tension, at 20^oC, dyn/cm..	20	10	21	22
Flash temperature mean, ^oC,.......	—40	—35	—30	—30
Spontaneous combustion temperature (droplet method) mean, ^oC........	470	440	400	300
Temperature limits for explosion-hazard mixtures at sea level, ^oC:				
lower.	—40	—35	—30	—30
upper.	—10	— 5	0	0
Concentration limits of explosion-hazard mixtures on the earth, % by volume.	0,98—5,48	0,98—5,48	0,89—5,76	0,79—5,76
Limits of pressure of the saturated vapors at which explosion-hazard mixtures are formed, mm Hg.	8—95	8—95	8—95	8—95
Solubility of air in gasoline at 20^oC, average on the earth, % by volume.	18	16	15	14
Solubility of water in gasoline at 20^oC average, %.	0,010	0,006	0,005	0,005
Solubility of gasoline in water at 20^oC, average, %.	0,001	0,001	0,001	0,001
Elementary composition, %:				
hydrogen.	16	15	15	14,5
carbon.	84	85	85	85,5
Group chemical composition:				
paraffins.	40—50	30—40	30—40	30—50
naphthenes.	30—40	40—50	40—50	40—50
aromatics.	15—25	15—25	15—25	15—20
unlimited.	1—2	1—2	1—3	1—3
Viscosity, kinematic at 20^oC, cSt..	0,40	0,45	0,45	0,50
Specific electrical conductivity:				
Ω^{-1}.	10^{-12}	10^{-12}	10^{-12}	10^{-12}
cm^{-1}	10^{-15}	10^{-15}	10^{-15}	10^{-15}
Rate of burnout of gasoline from a surface in a reservoir, mm/min...	2,2	2,0	1,9	1,8
Rate of burnout of gasoline from a surface average, kg/m^2.	95	92	91	90
Fire-extinguishing concentrations of inert gases (according to the data of P. G. Demidov), % by volume:				
carbon dioxide gas.	23	23	23	23
nitrogen.	31	31	31	31
Toxicity of the gasoline vapors and permissible concentrations, mg/l.	0,3	0,3	0,3	0,3
Temperature of a heated surface which will ignite gasoline upon contact, average, ^oC.	570	540	500	430

CHAPTER VI

FUELS FOR SUPERSONIC TRANSPORT AIRCRAFT

In the near future supersonic passenger aircraft will appear
on the lines of civil aviation.

Designers, scientists, engineers-exploiters are now working
to make supersonic aircraft as reliable, durable, and economic, as
subsonic aircraft. Among these problems one of the main ones is the
problem of the correct selection of fuel.

The distincitve peculiarity of the fuel system of a supersonic
aircraft is its considerably greater thermal strength. As a result
of aerodynamic heating, and also due to the heat removed from the
various working bodies (oil, hydraulic fluids, etc.), the fuel
temperature can rise to 150-160°C while in subsonic aircraft it rarely
rises above 50-80°C. In the fuel tanks of a supersonic aircraft,
where the fuel is located for a prolonged period of time, its temper-
ature toward the end of a flight can rise to 125-130°C (at M = 2.5).
In the fuel tanks of a subsonic aircraft the fuel in the process of
flight is cooled to -20-30°C. Thus, fuel for supersonic aircraft
should retain its operational properties at high (up to 160-180°C)
temperatures for a prolonged time. On a supersonic aircraft the fuel
is heated to high temperatures during flight at supersonic speeds.

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On sections of the flight from takeoff to the penetration of the supersonic barrier the fuel is found at relatively low temperatures, and at the moment the power plants are started on the ground in winter it can be at negative temperatures. Thus, fuels for supersonic aircraft should retain their operational properties even at low temperatures (to -60°C).

It is known, that in the bulk of operational expenses the portion of the expenses for fuel is considerably greater for supersonic aircraft, than for subsonic. Therefore, even at modern prices for jet fuels in the economics of supersonic aircraft the cost of fuel will occupy a larger place than in the economics of subsonic aircraft. The economy of supersonic aircraft in many respects is determined by the cost of the fuel being used.

1. Thermal Stability of Petroleum Fuels

Modern jet fuels upon heating to temperatures of 50-80°C do not substantially change their operational properties. During heating to higher temperatures the hydrocarbons of a fuel and the heteroorganic compounds undergo deeper oxidation. The depth of oxidation and the quantity of solid insoluble products of oxidizing decay formed increase with an increase in the temperature of the fuel. At a certain temperature sedimentation in the fuel reach a maximum size and then circulation of the fuel through the filters can cease. A further increase in the temperature of the fuel leads to a decrease in sedimentation, and at rather high temperatures sedimentation stops. Figure 63 shows the influence of the temperature of a fuel on the formation of insoluble deposits. As can be seen, fuels different in their physicochemical properties, have a different tendency towards the formation of insoluble deposits.

The strongest influence on the amount of insoluble deposits being formed in the fuel is shown by the concentration of oxygen both in a gas medium above the fuel, and dissolved in the fuel. If

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we remove all the dissolved oxygen from the fuel and place the fuel
into an inert gas medium, then sedimentation practically ceases.
Figure 64 shows the influence of the concentration of oxygen in a
gas medium on the formation of insoluble deposits. Removing the
oxygen from the fuel and filling the space above the fuel with inert
gases (nitrogen) is a very effective method of fighting sedimentation.
Table 28 shows that if we substitute nitrogen with 1.2% oxygen for
the air above the fuel, then under equal temperature conditions sedi-
mentation decreases ten times.
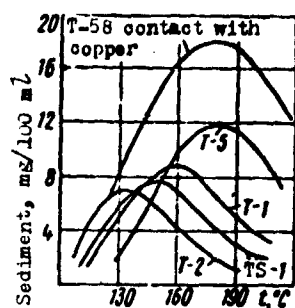
Fig. 63. Influence of the temperature on the
formation of insoluble deposits in jet fuels.
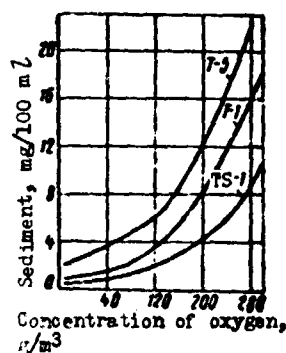
Fig. 64. Influence of the concentration of oxygen
in a gas medium on the formation of insoluble
deposits in fuels at 150°C in contact with bronze.

Under operational conditions to completely insulate the fuel from
oxygen is practically impossible, therefore it is not possible to
completely avoid oxidation of the fuel components.

A considerable effect on the amount of deposits being formed in
the fuel at elevated temperatures is exerted by metals. Figure 65
shows the effect of metals on the formation of insoluble deposits in
the fuel TS-1 at a temperature of 150°C. The greatest effect is
shown by copper, bronze, and brass, i.e., copper and its alloys.

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Table 28. Influence of a gas medium on the formation of insoluble deposits in fuels.

Temperature, °C	Quantity of deposits in the fuel, mg/100 ml		
	TS-1	T-1	T-2
In air			
125	3.2	3.8	2.0
150	13.7	14.0	9.1
200	6.3	7.0	3.4
250	4.3	5.2	1.9
In nitrogen containing 1.2% oxygen			
125	0.7	0.6	0.2
150	1.2	1.4	0.2
200	0.8	0.9	0.2
250	0.4	0.6	0.1
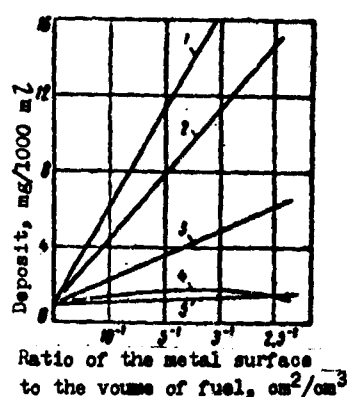
Fig. 65. Influence of metals on the formation of deposits insoluble in TS-1 fuel at 150°C: 1 — copper; 2 — bronze VB-24; 3 — brass L-62; 4 — duraluminium D1T; 5 — steel 12KhNZA.

Recently capital studies have been conducted and are being conducted to clarify the effect of the composition of jet fuels on their thermal stability. As we know, fuels consist of a hydrocarbon part, heteroorganic compounds, mechanical impurities, and water. Let us examine the effect of the separate component parts of a fuel on sedimentation at elevated temperatures.

The smallest quantity of deposits is formed during the oxidation of alkane-cyclane hydrocarbons. Even during oxidation for 6 h at a temperature of 150°C a noticeable quantity of deposits is not formed and only prolonged (more than 6 h) oxidation leads to the formation of deposits. Aromatic hydrocarbons during oxidation form a considerable quantity of insoluble deposits and resins. Moreover their

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quantity increases with an increase in the amount of rings in a molecule of aromatic hydrocarbons. The effect of the hydrocarbon composition can be illustrated by the data in Table 29.

Table 29. Thermooxidation stability of the hydrocarbons in jet fuels.

Fuels and hydrocarbon groups	Sediment, mg/100 ml	Resin deposits on bronze, g/m²	Corrosion, g/m²
TS-1			
Deresinated fuel........................ .	4,0	0,2	0,2
Alkane-cyclone fraction................. .	0,0	0,0	0,0
Aromatic fraction of a small cyclic recurrence....................... .	2,8	0,2	0,8
Aromatic faction of an increased cyclic recurrence................... .	4,9	0,5	0,8
T-1			
Deresinated fuel........................ .	5,8	0,2	0,4
Alkane-cyclane fraction................ .	0,0	0,0	0,0
Aromatic fraction of a small cyclic recurrence...................... .	3,1	0,1	0,2
The aromatic fraction of an increased cyclic recurrence................ .	7,0	0,3	0,4

If we limit the amount of aromatic hydrocarbons in a fuel, especially those of increased cyclic recurrence, then the hydrocarbon part of the fuel will have high thermal stability. A considerable decrease in the thermal stability of fuel occurs because of the various heteroorganic compounds (sulfurous, nitrides, oxygen).

The strongest influence on the thermostability of fuel and the corrosion of metals is shown by the sulfurous compounds. Figure 66 shows the effect of mercaptans on the thermal stability of TS-1 fuel at 150°C and its corrosion activity.

With an increased content of mercaptans to 0.01% sedimentation increases 6-8 times. Elementary sulfur, thiophenes, thiophanes, sulfides, and disulfides caused considerable deterioration of the thermooxidation stability of fuel. Other conditons being equal, the negative effect of sulfur-organic compounds on the thermooxidation stability of fuel is determined by the structure of their hydrocarbon radical. Table 30 gives the limiting concentrations of sulfurous compounds in a fuel. Higher than these amounts the thermal stability

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of a fuel sharply deteriorates. The given tables must be taken as particularly approximate, showing the relative role of various sulfur-organic compounds.
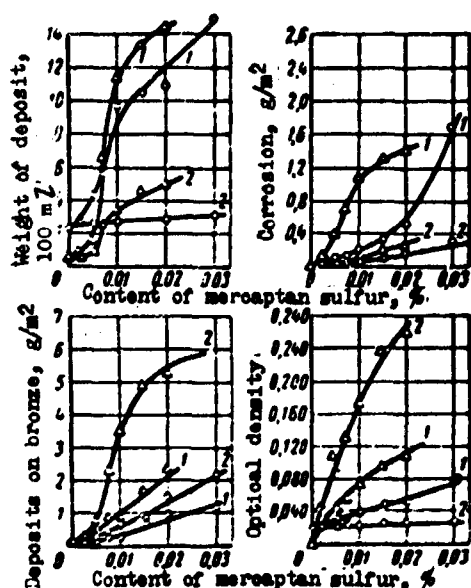
Fig. 66. Influence of mercaptans on the thermooxidation stability and the corrosion activity of TS-1 fuel at 150°C: 1 — hydrogenated TS-1 fuel + secondary octylmercaptan; 2 — hydrogenated TS-1 fuel + thiophenal; o-o — in brass vessels; ▲-▲ — in glass vessels.

Table 30. Limiting content of sulfurous compounds in a fuel.

Sulfurous compounds	Temperature of boiling out of the fuel, °C	Acceptable content of sulfurous compounds, % by weight (for sulfur)
Mercaptans..........................	100	0.005
	150 and more	0.002
Thiophenes..........................	100—150	0.20
	150 and more	0.10
Aromatic sulfides...................	100	0.05
	150	0.05
Aliphatics sulfides.......... ...	100	0.10
	150	0.08
Disulfides........................	100	0.05
	150	0.02

All sulfurous compounds according to their effect on the decrease in the thermooxidation stability of a fuel are placed in the following order: mercaptans, disulfides, sulfides, thiophenes, thiophanes.

A negative effect on the thermal stability of a fuel is shown by resins. As a rule, the more resin in a fuel, the worse its thermooxidation stability. However some resinous substances that

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pass over into fuel from oil, at determined concentrations have
a positive effect, i.e., decrease the amount of deposits being
formed. The aforesaid is well illustrated by Fig. 67.
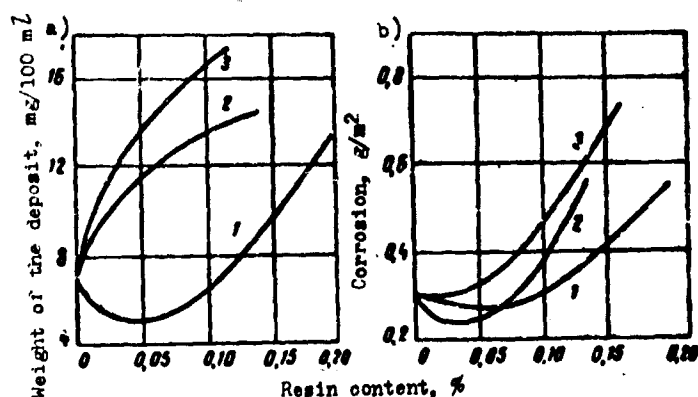
Fig. 67. Influence of resinous substances on the stability of TS-1
fuel (a) and its corrosion activity (b): 1 — resins separated out
from fresh TS-1 fuel; 2 — resins separated out from preliminarily
deresinated fuel after a year of storage; 3 — resins separated out
from secondarily deresinated fuel after a year of storage.

Nitride compounds in jet fuels are contained in quantities not
more than 0.05-0.1% and practically do not exert a substantial effect
on the thermooxidation stability of a fuel. A large influence on
the thermal stability of fuels is shown by water and microimpurities.
Removal of them from the fuel always leads to an increase in its
thermooxidation stability.

2. Methods of Increasing the Thermal Stability of Fuels for Supersonic Aircraft

The thermooxidation stability of the fuels for supersonic aircraft
can be increased by the following methods: by improving the technology
of obtaining and cleaning fuels at oil-refining plants; by using
effective additives; by removing microimpurities and water from the
fuel; by eliminating contact of the fuel with the oxygen in the
air and with catalytically active metals.

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Of the technological methods of increasing the thermal stability of fuels the most promising are hydrocracking and hydrofining. During the hydrocracking of the gas-oil fraction of oil at a temperature of 260-440°C and hydrogen pressure of 35-175 atm jet fuel is obtained which possesses high thermal stability.

During hydrofining the sulfurous compounds and part of the products of oxidation and the resins are removed from the fuel. In this case the thermal stability of the fuel increases considerably.

It is possible to partially eliminate contact of the fuel with oxygen by filling the vapor space above the fuel with inert gases. An increase in the thermal stability of the fuel is attained by improving the fineness of filtration before putting it into the tanks of an aircraft.

Perhaps the most effective and most promising method of increasing the thermal stability of fuels for supersonic aircraft is the development and use of effective additives. Today many studies are being conducted for this purpose. Hundreds of organic and inorganic compounds, known and specially synthesized, have been studied.

Today, two classes of compounds have received the greatest recognition as additives for increasing the thermal stability of jet fuels: aliphatic high-molecular secondary amines; copolymers of the ether of methacrylic acid.

3. Composition and Basic Properties of Fuels for Supersonic Passenger Aircraft

Presently it is still not possible to reliably name the grades of fuels for supersonic passenger aircraft. But it is possible to assume what they will be. Most probably they will be kerosenes, both the products of direct distillation, and of hydrocracking,

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subjected to thorough hydrofining. Heteroorganic compounds, micro-impurties, and water will be removed to the maximum from the fuel. The hydrocarbon part will consist mainly of alkanes and naphthenes. The temperature limits of boiling out will be determined by the conditions of use in the aircraft and by economic considerations. It is possible to assume that the fractional composition of the fuel will be found within the limits 150-300°C.

The fuels will contain additive which increase the thermooxidation stability and the antiwear properties.

Grade T-6 fuel according to GOST 12308-66 most completely fulfils the requirements for fuels for supersonic passenger aircraft (see Table 18, Chapter IV).

C H A P T E R   VII

FUELS FOR ROCKET ENGINES

The first rocket engines operated on solid fuel — pressed powder. As a result of the large burning rate of the powder and the relatively small reserve of it, being limited by the sizes of the combustion chambers, the period of operation of a powder rocket engine is very short (0.1-25 s), and the thrust force developed by the engine is difficult to regulate.

Liquid fuel rocket engines, the idea of which was proposed by K. E. Tsiolkovskiy, opened the new perspectives in the development of rocket technology because they possess substantial advantages over powder rocket engines.

K. E. Tsiolkovskiy comprehensively investigated the magnitude of the thermal effects of the combustion reaction of various elements and formulated the basic requirements for fuels for liquid fuel rocket engines.

Great work in the creation and study of rockets with liquid fuel rocket engines and fuels for them was accomplished by the native scientists V. P. Vetchinkin, G. E. Langemak, F. A. Tsander, and others.

Among the researchers in foreign countries a substantial contribution to the development of rocket technology was introduced by Esnault-Peltrie (France), Goddard (USA), Sänger (Austria), and others.

The fundamental distinction of a rocket engine is the fact that it operates independent of the surrounding medium. During combustion of the fuel in a rocket engine the oxygen in the air is used not by a special oxidizer, reserves of which should be on-board the craft. For fuels, rocket engines can use substances, which are able to give off thermal energy, and gaseous products as a result of decomposition, association, nuclear processes, or other reactions without using an oxidizer.

In connection with this a rocket engine can operate independent of the surrounding medium on the earth, in airless space, underwater, etc.

1. The Classification of Propellants for Rocket Engines

Propellants according to state of aggregation are divided into liquid and solid (powder). Liquid propellants are divided into two classes by method of use: two-component and single-component. Under propellant components we imply each of the substances, separately supplied to the combustion chamber of liquid fuel rocket engine. The diagram of the classification of propellants is given in Fig. 68.

Two-component propellants consist of two components which are separately supplied to the combustion chamber of the engine: fuel and an oxidizer. Propellants of this class are most widely used because separate storage of the fuel and the oxidizer in separate tanks considerably decreases the danger of explosions and it facilitates the conditions of use, storage, and transport of the propellant. Furthermore, the use of two-component propellants

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considerably expands the possibilities of selecting substances, suitable for use as a fuel and an oxidizer which makes it possible to create the most effective fuel mixtures.
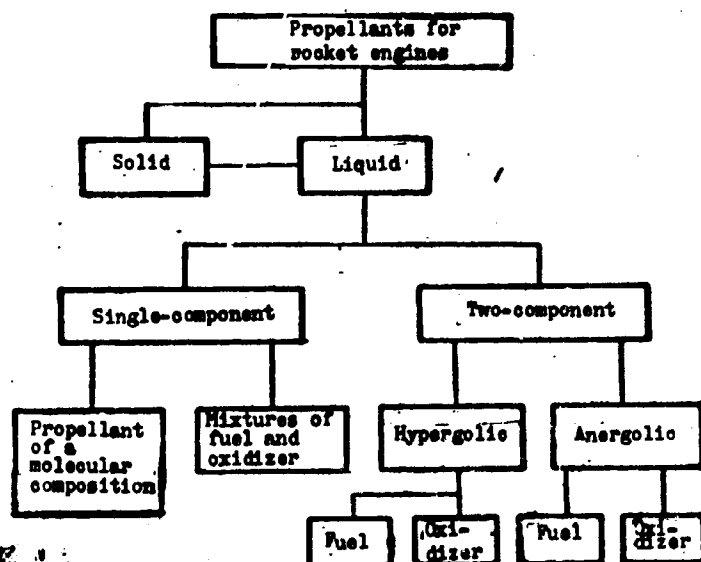
Fig. 68. Classification of propellants for rocket engines.

Two-component propellants can be divided into two groups according to the method of ignition in the engine: hypergolic and aneregolic. Upon contact of some fuels and oxidizers at ordinary temperatures a chemical reaction takes place with the liberation of such a quantity of heat which is sufficient to ignite the fuel mixture. Such propellants received the name hypergolic.

Propellants whose liquid components (fuel and oxidizer) do not ignite upon contact belong to the second group of propellants, and special devices are required to ignite them.

Propellants which do not require an oxidizer supplied from the outside belong to single-component propellants. The use of single-component propellants makes it possible to considerably simplify

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the fuel system of an engine. However their use for the time being is limited because of their explosiveness and relatively low heat of combustion.

Propellants for liquid fuel rocket engines are divided into basic, starting, and auxiliary according to their purpose.

Basic propellants are called the propellants used directly for operation of the engine as the basic source of energy and the working body; starting — used for the ignition in the combustion chamber of anergolic basic working propellants while starting the engine. Propellants used for supplying power to the auxiliary units of a liquid fuel rocket engine (turbopump unit, liquid accumulators of the basic fuel supply system, etc.) belong to the auxiliary fuels.

2. Requirements Shown for the Propellants for Liquid Fuel Rocket Engines

The history of the development of liquid fuel rocket engines to a considerable extent represents the history of searches and testing of substances suitable for combustion in an engine and providing for its effective operation. Propellants for liquid fuel rocket engines should provide for easy starting, steady combustion, effective cooling of the combustion chamber, uninterrupted operation of the fuel system, safety of access to them during storage and transport. The effectiveness of a propellant in the relationship of providing the most economic operation of an engine is usually evaluated by the size of the effective rate of discharge of the products of combustion.

The rate of discharge of the gaseous products of combustion from the nozzle of a liquid fuel rocket engine can be determined from the following expression:

$$u = \sqrt{\eta_i 2g \frac{k}{k-1} pV}$$

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or

$$u = \sqrt{\eta_t 2g \frac{k}{k-1} RT}.$$

where η_t — the thermal efficiency of the engine; g — free fall acceleration, m/s^2; $k = \frac{C_p}{C_v}$ — adiabatic curve indicator; p — the pressure of the gases in the combustion chamber, kgf/cm^2; V — the volume of gases formed during the combustion of 1 kg of propellant (under standard conditions), m^3/kg; R — the gas constant of the products of combustion depending on the composition of the gases, kg·m (kg·deg); T — the temperature of combustion of the propellant, $^\circ$K.

From the equations it follows that the rate of discharge of the products of combustion increases with an increase in the specific volume of gases (gas formation) and the temperature of burning of the propellant and depends on the gas constant R.

For the characteristic of a propellant we use the idea of specific thrust $R_{уд}$, i.e., the engine thrust related to a unit of the per second expenditure of propellant. Specific thrust is determined according to the following equation:

$$R_{уд} = 9{,}33 \sqrt{\eta_t H}$$

or

$$R_{уд} = 9{,}33 \sqrt{\eta_t H \rho}.$$

where H — the heat of combustion of the propellant, kcal/kg; η — thermal efficiency; ρ — the propellant density, kg/l.

The higher the temperature of combustion and the density of the propellant, the larger the value of the specific thrust of an

engine. Figure 69 shows how the specific thrust of an engine changes depending on the heat of combustion of a propellant of a different density. Such a dependence between the heat of combustion and the density of the propellant becomes understandable if one considers that the specific thrust of an engine depends on the quantities of the products of combustion formed during the combustion of a unit of propellant, and on their temperature.
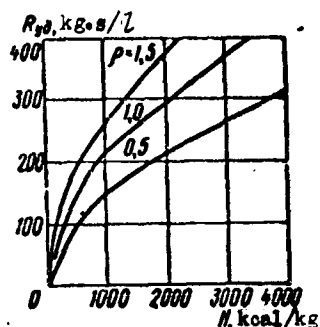
Fig. 69. Dependence of the specific thrust of a liquid fuel rocket engine on the heat of combustion and the density of the propellant.

When evaluating the **energy** characteristics of a propellant we consider the gas formation in standard liters (s.l.), i.e., in liters of gas at 20°C and 760 mm Hg, and the amount of heat liberated per 1 s.l. of gas. The basic energy characteristics of some propellants are given in Table 31.

The reliability of operation of a rocket engine in many respects depends on how its starting is accomplished. At the moment of a starting the propellant is ignited in the interval of time, equal to the period of delay of ignition, which depends on the type of propellant. During this time the fuel mixture accumulates in the combustion chamber, the instantaneous ignition of which leads to an explosion; the force of this explosion depends on the amount of propellant that has entered the combustion chamber at the moment of ignition. At long ignition delays this will lead to damage of the engine.

Table 31. Gas formation during the combustion of various propellants and the amount of heat liberated per 1 s.l. of gas (not allowing for dissociation).

Fuel	With oxygen			With fluorine		
	Gas formation, s.l.		amount of heat liberated per 1 s.l. of gas, kcal	Gas formation, s.l.		amount of heat liberated per 1 s.l. gas, kcal
	from 1 kg of fuel	from 1 kg of stoichiometric mixture		from 1 kg of fuel	from 1 kg of a stoichiometric mixture	
Hydrocarbons:						
paraffins...................	3400	760	3,12	5012	540	4,08
naphthenes, olefins........	3190	720	3,28	4780	520	4,00
benzene....................	2580	630	3,74	3430	412	5,08
gasoline...................	2790	665	3,51	3900	450	4,82
kerosene...................	3160	720	3,19	4720	520	4,06
	3160	720	3,16	4720	520	4,03
Alcohols:						
methyl.....................	2440	980	1,91	2785	610	3,84
ethyl......................	2660	860	2,41	3370	565	3,98
Nitrogen containing:						
ammonia....................	2620	1010	1,56	4580	1050	2,22
hydrazine..................	2090	1045	1,74	3480	1030	2,28
dimethylhydrazine..........	2610	840	2,68	4090	680	3,38
triethylamine.............	3090	755	3,07	4740	570	3,91
xylidine..................	2740	680	3,35	4230	515	4,16
Boron-containing:						
pentaborane...............	2460	830	5,48	4920	865	6,00
decaborane................	2190	795	5,88	4350	840	6,48

The shorter the period of ignition delay, the smoother the engine starting is. Therefore one of the requirements given for a propellant for liquid fuel rocket engines, is the constancy of the ignition delay period of the propellant according to the composition of the mixture at a sufficiently low value of it according to the absolute value. Besides this, to provide for reliable starting of a liquid fuel rocket engine it is necessary that the propellants have wide concentration limits of ignition and good volatility.

One of the requirements given for liquid fuel rocket engines, is to provide for a constant amount of thrust for a given expenditure of propellant, i.e., to provide for a steady mode of combustion. During the burning of a propellant in the combustion chamber of a liquid fuel rocket engine fluctuations in pressure (up to 50% and

more with a frequency of from 10 to 5000 s^{-1}) can be observed. Vibrations with a frequency on the order of 220-360 s^{-1} belong to the category of low-frequencies and do not cause specifice harm to the engine. High-frequency vibrations (600-1500 s^{-1}) can cause failure of the engine.

The appearance of vibrations during unstable burning, apart from physicomechanical factors, is explained by the presence of a period of induction, i.e., an interval of ti e between the change in the amount of the propellant supply and the subsequent change in pressure in the combustion chamber as a result of the combustion of propellant. The size of the period of induction depends on physical processes (dispersion, mixing, vaporization) and on the chemical reaction of the components. With a decrease in the period of induction the possibility of the appearance of an unstable burning condition decreases.

The greatest period of induction can be expected in for anergolic propellants — oil products in connection with the large period of time necessary for their vaporization in the combustion chamber.

A liquid fuel rocket engine is a very thermally stressed device. In the relatively small volume of its combustion chamber the large quantity of propellant is burned up at a high rate. In connection with this the combustion chambers are cooled either by pumping the fuel or oxidizer through the cooling jacket which then enter the injectors of the engine (regenerative cooling), or by creating a thin film of fuel or oxidizer on the interior surface of the combustion chamber and the nozzle, which evaporating, protects the walls, decreasing the amount of heat conducted to them frc¬ the products of combustion (film cooling). In certain cases combined (film and regenerative) cooling is_used.

Since propellant is used simultaneously as a cooling liquid, additional requirements are set forth for it: elevated thermal

stability, good heat capacity, a sufficiently high boiling point, high heat of vaporization, low buoyancy of the vapors.

Propellants for liquid fuel rocket engines should possess sufficient **chemical** stability and good pumpability. Therefore, the propellants must have the low freezing temperatures and an optimum level of viscosity.

Besides sufficiently high physical and chemical stability, it is advisable, that the components of a propellant for a [ZhRD] (ЖРД) liquid propellant rocket engine would be safe in handling, not cause burns and poisonings, and be produced on an industrial scale. Today there are no propellants which completely correspond to all the requirements set forth for them. In practice it is necessary to select for use such propellants which give the best results for the given operating conditions of the liquid fuel rocket engine.

3. Fuel for Liquid Fuel Rocket Engines

Fuel for liquid fuel rocket engines can be divided into the following groups according to chemical composition: hydrocarbons and their mixtures (gasoline, kerosene, ligroin); alcohols (methyl, enthyl, and others); amines (aniline, triethylamine, xylidine); hydrazones and their derivatives.

Furthermore, fuels can be liquid ammonia, liquid hydrogen, various metals and their compounds.

Hydrocarbon fuels obtained from petroleum are the cheapest and provide a wide material raw base. The characteristic peculiarity of hydrocarbon fuels is the high heat of combustion and for this reason very high temperatures appear in the combustion chamber which hinders the selection of stable structural materials.

Engines have been designed today which make it possible to use hydrocarbon fuels both with liquid oxygen, and with oxidizers based on nitric acid and hydrogen peroxide.

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Usually aviation kerosene, cracking kerosene, gasoline, and other products of the refining of oil, coal, and shales are used in liquid fuel rocket engines. The most preferable are the kerosenes since they have a greater density than gasoline.

Ordinary wide-fraction aviation fuel serves as the fuel in the liquid fuel rocket engines of the American "Nike" and "Atlas" rockets.

In recent years in the USA the kerosene Rp-1 has been produced especially for liquid fuel rocket engines; it has an insignificant content of aromatic and unsaturated hydrocarbons which boil away at a temperature of 195-275°C. The Rp-1 kerosene was used with nitric acid or liquid oxygen in the "Thor" rockets, and in the first stages of the "Vanguard" and "Saturn" rockets.

The alcohols found a use as fuel for liquid fuel rocket engines in conjunction with such oxidizers, as liquid oxygen and hydrogen peroxide. Possessing the considerably less heating capacity in comparison with hydrocarbons, alcohols are considerably inferior to them in effectiveness of combustion in liquid fuel rocket engines.

Upon the combustion of alcohols a lower temperature is developed which facilitates the creation of a reliably operating engine. Furthermore, alcohols have a higher heat capacity and latent heat of vaporization than do oil-products. This circumstance, and also the high relative content of alcohols in prepared fuel mixtures (up to 40-50%) makes it possible to use alcohols with success for cooling the walls of the combustion chamber. Ethylene alcohol (ethanol) C_2H_5OH has a boiling point of 78°C and a very low freezing temperature of -114. Rectified alcohols containing about 6% water by weight with a density of about 0.814 or water solutions of alcohol of an even smaller concentration are usually used. When mixing ethanol with water due to hydration (the formation of groups of molecules

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$C_2H_5OH \cdot xH_2O$) a decrease in the volume occurs and the density rises. The addition of water to alcohol, under determined conditions can play a positive role because it decreases combustion temperature and simultaneously increases the gas formation and the mass of expelled particles.

The highest alcohols have a higher density and boiling point in comparison to the lower, however the lower alcohols find the greatest practical use: methyl, ethyl, or their mixtures, which are the cheapest and most easily secured from a wide industrial base.

The rather high boiling temperatures and low freezing temperatures of alcohols makes it possible to use them in a wide range of operational temperatures. Alcohols, as also hydrocarbons, are distinguished by their insignificant corrosive activity with respect to metals. Therefore the tanks and the fuel apparatus of an engine are manufactured from ordinarily available and inexpensive materials. The good operational properties, relatively low burning temperature, high burning stability, and good cooling capacity determined the selection of alcohols as fuels in the early period of the development of liquid fuel rocket engines. Alcohols as rocket fuel did not lose their value until now.

Nitrogen containing fuel. The problem of creating a reliably operating engine is successfuly solved when using hypergolic fuels with an oxidizer with a small period of delay for spontaneous combustion. The advantage of hypergolic propellants is also the fact that when they are used the starting system of the engine is simplified because in this case special ignition system is not required. In the operating mode such propellants burn more steadily with less pulsations and vibrations, than forced ignition propellants.

A large quantity of the formulas for porpellants which self-ignite in a reaction with nitric acid, was created on the basis of

amino compounds. Amino compounds or amines, are called derivatives of ammonia, in a molecule of which one or several atoms of hydrogen have been substituted by hydrocarbon radicals.

Amines refer to a number of better fuels for liquid fuel rocket engines. They possess a number of positive qualities: low ignition temperature, large gas formation, relatively large density, wide concentration limits of ignition, and a small ignition delay period. Good inflammability and high combustion stability caused the very wide use of amines as fuels for liquid fuel rocket engines, despite their relatively high cost. Aniline, triethylamine and a xylidine received the greatest practical use as fuel. Amines possess sharp unpleasant smells. They are all deadly poisons.

Aniline $C_6H_5NH_2$ — oily liquid with a boiling point of $184°C$, freezing $-6°C$ and a relative density of 1.02.

Xylidine (aminooxylol) $C_6H_3NH_2(CH_3)_2$ — a high-boiling oily liquid (boils at $210°C$) with a rather low freezing temperature ($-54°C$). The density of xylidine is approximately 0.98.

Triethylamine $N(C_2H_5)_3$ — a relatively light volatile liquid with a density at $20°C$ of 0.728, boiling point $90°C$, freezing $-115°C$). In comparison with other amines triethylamine shows the sharpest striking effect on the central nerve system. A mixture of 50% xylidine and 50% triethylamine is known by the name "tonka."

Liquid ammonia can be used as fuel for a ZhRD. It is very profitable to use liquid ammonia in conjunction with liquid fluorine. Such a fuel makes it possible to obtain a high specific thrust from an engine (340-350 kg·s/kgf). The gain in effectiveness when using ammonia as a fuel is connected with the better thermodynamic properties of the products of the combustion of the propellant (low molecular weight, a considerable content of diatomic gas).

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Under ordinary conditions ammonia is a colorless, easily liquified gas with a characteristic sharp smell. Under a pressure of 6-7 kgf/cm^2 under ordinary conditions ammonia is in a liquid state. The boiling point of ammonia — 33.4°C, freezing -77.7°C, density at the boiling point 0.68 g/m^3. Ammonia is produced industrially in large quantities, therefore as a propellant it is relatively inexpensive. The substantial deficiency of ammonia that hampers its use is the low boiling point.

Of the nitrogen containing compounds finding a use as fuels for liquid fuel rocket engines, an important place is occupied by hydrazine and its derivatives: hydrazine hydrate, dimethylhydrazine, and others.

Gidrazin (N_2H_4) — a viscous poisonous liquid; its density at 20°C equals 1.01, boiling point — 113°C. The freezing temperature of hydrazine (-2°C) from the point of view of an operational evaluation is completely unsatisfactory.

Hydrazine forms hydrazine hydrate N_2H_4OH or $N_2H_4 \cdot H_2O$ of an alkaline character with a density of 1.03 with water; the boiling point is 118°C and the considerably lower freezing temperature which is acceptable for use (-40°C). Both hydrazine and hydrazine hydrate have a relatively low calorific value, but in return require a small quantity of oxidizer for their combustions provide a large gas formation, a low temperature condition, and give insignificant heat losses to dissociation.

Dimethylhydrazine $N_2H_2(CH_3)_2$ possesses a higher calorific value than hydrazine. Dimethylhydrazine — a transparent colorless poisonous liquid. Its density — 0.795, boiling point — 63°C, freezing -58°C. Dimethylhydrazine mixes well with ethyl alcohol, gasoline, kerosene, and water; it is hygroscopis. Its vapors are an explosion-hazard over wide concentration limits.

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Hydrazine with liquid oxygen was used in the engine of the first stage of the rocket, with which in 1957 USA launched its artificial earth satellite.

Dimethylhydrazine easily selfs-ignite with oxidizers based on nitric acid. With liquid oxygen it ignites from an outside source of ignition. The period of delay of the spontaneous combustion of dimethylhydrazine with fuming nitric acid is very low (several milliseconds) and provides easy starting and operational stability of the engine under various operating conditions.

Liquid hydrogen as a fuel. The high energy qualities of liquid hydrogen have been known for a long time. The idea of using it in a mixture with oxygen as a propellant for liquid fuel rocket engines was expressed for the first time by K. E. Tsiolkovskiy.

Liquid hydrogen in a mixture with liquid oxygen is easily ignited on with a short ignition delay period, has a very high heat of combustion equal to 3010 kcal/kg, and wide concentration limits of ignition. At the same time such a propellant is distinguished by large gas formation (1240 l/kg).

Gaseous hydrogen is the lightest of the gases. Liquid hydrogen — this is a transparent colorless, extremely light mobile liquid with a very low boiling point (-253°C) and freezing point (-257°C) and low density (0.007).

The use of liquid hydrogen is hampered by its too low density, complexity of storage, and access to it. However, considering the high energy properties of hydrogen, it is considered as a very promising fuel, especially for the engine rockets of a large radius of action.

4. Oxidizers for Liquid Fuel Rocket Engines

The components of rocket propellants intended for oxidation of the combustible substances in the combustion chamber of the engines

are called oxidizers. The properties of a rocket propellant are basically determined by the properties of the oxidizer because its consumption by a liquid fuel rocket engine is considerably (2-4 times) greater than the fuel component. Oxidizers can be divided in the following manner: liquid oxygen and ozone; concentrated hydrogen peroxide; nitric acid and the oxides of nitrogen; tetranitromethane; liquid fluorine and fluorine compounds; chloric acid and the oxides of chlorine.

Liquid oxygen. Propellants which use liquid oxygen as an oxidizer as a rule, are not hypergolic.

Under normal conditions oxygen is a gas with critical temperature of -118.8°C and critical pressure of 49.7 kgf/cm^2. Liquid oxygen is a bluish liquid of specific weight 1.14, boiling at -183°C and freezing at -219°C. The most important advantages of liquid oxygen as an oxidizer, besides its high energy characteristics, are its non-toxidity, cheapness of manufacture, and practically unlimited raw material resources.

When using liquid oxygen lubricants and oils of an organic nature should not be used due to the danger of explosions.

Ozone – one of the strongest oxidizers. It is the allotropic modification of oxygen. A molecule of it contains three atoms of oxygen. Liquid ozone has a dark-blue color, boils at a temperature of -112 and freezes at a temperature of -251°C, its density equals 1.46.

Basic deficiencies of ozone, besides the low boiling temperature are its explosiveness and high toxicity, it is susceptible to spontaneous decomposition with the liberation of a large amount of heat according to the equation $2O_3 \rightarrow 3O_2 + 69$ kcal.

Gaseous ozone can decompose with an explosion. The use of pure liquid ozone as an oxidizer for liquid fuel rocket engines has

been hampered up to now because of its tendency towaras explosive
decomposition. One of the methods of stabilizing ozone is to use
it in a mixture with liquid oxygen (up to 30%).

A mixture of ozone with oxygen is not explosive and is stable
during storage. The effectiveness of liquid oxygen as an oxidier
grows proportionally to the ozone content in it. The presence in
liquid oxygen of ozone, which is able upon decomposition to give up
an active atom of oxygen, facilitates an increase in the rate of
burning.

Concentrated hydrogen peroxide is widely used in rocket technology
as an oxidizer and as a means of obtaining the steam necessary
rotate the turbine of the turbopump unit of some types of rockets.
When using peroxide as an oxidizer an additional thermal effect is
otained upon combustion of the propellant in the combustion chamoer.
This effect is caused by the fact that a molecule of hydrogen
peroxide before introduction into the oxidation reaction decomposes
with the liberation of a considerable amount of heat.

Hydrogen peroxide is mixed up in any ratio with water, ethyl,
and methyl alcohols. One of deficiencies of concentrated hydrogen
peroxide is the high (-0.89°C) freezing temperature which hampers
its use under wintry conditions. Dry hydrogen peroxide is thermally
unstable and is very sensitive to different kinds of contaminants
Dropping various impurities into peroxide (dust, rust, the salts of
heavy metals, and others) leads to a sharp increase in the rate of
decomposition of the hydrogen peroxide and its strong heating. The
best guarantee of stability o   /drogen peroxide is to provide for
its purity both during production, and in the processes of storage,
transport, and pumping.

Today hydrogen peroxide stabilizers have been developed.
Orthophosphoric and pyrophosphoric acids and their salts are used

as stabilizers. Mixtures of concentrated hydrogen peroxide with organic substances (benzene, toluene, alcohols) are explosive substances. Dropping concentrated hydrogen peroxide on to the skin causes severe burns. The best aid in this case is to wash the affected areas with large amounts of water.

Nitric acid — a colorless, highly mobile liquid with a molecular weight of 63 and a density of 1.52, boiling at a temperature of 86°C and freezing at -41.2°C. Anhydrous nitric acid is unstable even at negative temperatures. It decomposes according to the equation

$$4HNO_3 \rightarrow 4NO_2 + 2H_2O + O_2.$$

In connection with this there is always a certain amount of water and nitrogen oxides in concentrated itric acid. The chemical industry produces technical 96-98% nitric acid which is frequently called "white fuming acid." This is a heavy liquid of a straw-yellow color with a density of 1.49-1.50 at a temperature of 20°C. In air it fumes because of the formation of fine droplets of diluted acid with the moisture in the air.

Nitric acid in practice does not mix with a majority of hydrocarbons, nitric acid mixes with water in any ratio.

To increase the effectiveness of concentrated nitric acid as an oxidizer, and also to increase in thermal stability it is frequently used in a mixture with nitrogen tetroxide (about 20%). The acid, containing up to 20% nitrogen oxides is called "red fuming nitric acid." Th . is a heavy orange-colored liquid which fumes strongly in air as a result of the liberation of brown vapors of nitrogen dioxide. The basic deficiencies of nitric acid are its corrosive agressiveness with respect to a majority of metals, its capacity to destroy many materials of an organic origin, and its toxicity.

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Nitrogen tetroxide N_2O_4 presents the greatest practical interest of all nitrogen oxides. It is a stable product, and exceeds nitric acid in effectiveness. The deficiencies of nitrogen tetroxide are its narrow temperature range in the liquid state at atmospheric pressure (-11.2 — +21.2°C).

With respect to metals nitrogen tetroxide is considerably less active than concentrated nitric acid.

Tetranitromethane $C(NO_2)_4$ is a promising oxidizer which is more effective than concentrated nitric acid. In a molecule of tetranitromethane there is a large quantity of active oxygen. Tetranitromethane is a heavy mobile liquid of a greenish color with a sharp smell. Pure tetranitromethane has a density of 1.643 at a temperature of 20°C, it boils at 125°C and freezes at 13.8°C. Tetranitromethane at normal temperatures is a stable substance and can be stored for years without noticeable change. Only during heating above 100°C it partially decomposes forming nitrogen oxides and carbon dioxide gas. It is poorly soluble in water. The most important advantage of tetranitromethane over nitric acid is its low corrosion activity with respect to metals and alloys. Glass, stainless steel, aluminum, and lead do not corrode in tetranitromethane.

The substantial deficiency of tetranitromethane which prevents its use in the pure form is its high freezing temperature.

In connection with this it is recommended that tetranitromethane be used in a mixture with the nitrogen tetroxide. A mixture, consisting of 70% tetranitromethane and 30% nitrogen tetroxide freezes at a temperature below -25°C. In this case the energy properties of the oxidizer remain practically the same as in pure tetranitromethane.

Liquid fluorine and compounds of fluorine. Fluorine is one of the most reactive elements. This makes it a very promising rocket

oxidizer. It is strongest of all known oxidizers. In conjunction
with such fuels, as hydrazine or ammonia, it makes it possible, at
a pressure in the combustion chamber of 25 kgf/cm^2 to obtain a
specific thrust of about 305-316 kgf·s/kg. For comparison let us
note, that the propellants being widely used today for liquid fuel
rocket engines make it possible to obtain a specific thrust of only
about 230-2^{0}0 kgf·s/kg.

Free fluorine under standard conditions is a gas of a greenish-
yellow color with an unpleasant smell. Liquid fluroine is yellow in
color. Even at normal temperatures fluorine reacts energetically
with almost all organic and inorganic substances, moreover the
reaction takes place with the liberation of a large amount of heat
and frequently is accompanied by ignition.

Inert gases, fluorides of the heavy metals, teflons, and also
bismuth, zinc, tin, lead, gold, and platinum practically do not react
or react very insignificantly with fluorine. Cooper, chromium,
manganese, nickel, aluminum, stainless steel in the absence of
water are in practice stable in contact with fluorine due to the
formation of a durable protective film of the appropriate fluoride
on their surface.

One of deficiencies of liquid fluorine is its low boiling point
(-187°C) and high toxicity.

Of the derivatives of fluorine oxygen fluoride OF_2, chlorine
trifluoride ClF_3, bromine pentafluoxide BrF_5, and others can be used
as effective oxidizers.

P A R T   II

AVIATION OILS, LUBRICANTS AND SPECIAL LIQUIDS

C H A P T E R   VIII

THE GENERAL CHARACTERISTIC OF AVIATION OILS

1. Basic Information About Friction and Lubricants

The main purpose for lubricating any mechanism is to decrease the wear of the friction parts and to decrease the power being spent on friction. Besides this, lubricants accomplish a number of other important functions: they remove heat from the heated parts of machines, protect them from corrosion, they clean the space between the friction surfaces of the products of wear and mechanized impurities, etc.

In order to correctly select and to use oils, it i; necessary primarily to know the basic regularities of the processes of friction and wear of the machine parts, the conditions under which the oils operate, the quality, composition, and possible changes in the quality and the composition of oils during operation in engines.

During the operation of machine parts three types of friction are distinguished, differing from one another: fluid, boundary, and dry.

When two surfaces moving against each other are divided by a

layer of oil, fluid friction appears, i.e., friction between the layers and the molecules of oil. The coefficient of fluid friction lie within the limits 0.001-0.010. The laws of hydrodynamics can be applied to the film of oil which separates the moving parts, moreover the viscosity of the oil is, in this case, a paramount factor.

Presently the laws of the hydrodynamics of lubricants have been studied quite well.

N. P. Petrov, based on the law of Newton (for the friction of liquid bodies) and on his numerous experiments expressed mathematically for the first time the law of fluid friction and proposed the following simplified formula for practical use:

$$F = \frac{\eta S v}{h},$$

where F - the force of fluid friction, kgf; η - the absolute viscosity of the oil, $kgf \cdot s/m^2$; S - the area of contact of the friction bodies, m^2; v - the rate of movement of the friction surfaces, m/s; h - thickness of the lubricating layer, mm.

From the given formula it follows that with liquid lubrication (hydrodynamic lubrication regime), friction in a bearing depends only upon the viscosity of the oil and depends neither on the material of the shaft and the bearing, nor on the state of the friction surfaces.

The theory of fluid friction of N. P. Petrov was confirmed and developed by the works of N. Ye. Zhukovskiy, S. A. Chaplygin, O. Reynolds, A. Sommerfeld, L. Humble, N. I. Mertsalov, A. N. D'yachkov, A. I. Petrusevich, and others.

During fluid friction the reliability of a lubricant, or,

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that which is the same, the applied maximum force increases with an increase in the rate of motion of the friction surfaces and with an increase in the viscosity of the oil, which can be seen, having substituted into the afore-cited formula the size of the friction force expressed by the coefficient of friction and the applied load:

$$F = Nf,$$

where N - the applied maximum force, normal to the surface of friction, at which the fluid mode of the lubricant is still retained kgf; f — the coefficient of friction.

Then the expression for N takes the following form:

$$N = \frac{\eta S v}{hf}.$$

On the other hand, with an increase in the rate of motion of the friction surfaces and the viscosity of the oil the force of friction increases, i.e., the losses of power to friction increase. This contradiction is solved by selecting oil of the proper viscosity: for a rapidly revolving shaft in a bearing low viscosity oil is selected, for a slowly revolving shaft - a higher viscosity. The hydrodynamic mode of the lubricant is the most acceptable for friction parts because it provides for low wear of parts and small losses of power to friction.

However for many friction parts it is not possible to create the hydrodynamic condition of lubricant because of the structural peculiarities of the friction node. Furthermore, even in bearings calculated for operation under conditions of a liquid lubricant,

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over determined periods of their operation the hydrodynamic condition
of friction can be destroyed. The fact is that with an increase in
the load on the oil film, with a decrease in the viscosity of the
oil, or with a decrease in the rate of motion of the surfaces the
thickness of the film decreases.

With a decrease in the thickness of the oil film there comes a
moment, when separate unevennesses on the surfaces will begin to
appear through the film of oil leading to contact of the friction sur-
faces. The boundary condition of the lubricant sets in. With an
increase in the number of contact points the area of the boundary
lubricant will gradually be enlarged due to the decrease in the
liquid lubricant. Such a state, when along with liquid lubrication
boundary lubrication also takes place, has been called semiliquid
or combined lubrication.

Under the conditions of boundary lubrication the basic
characteristics of friction and wear are determined by the state of
a thin oil film adsorbed on the surfaces of friction. The stability
of thin boundary layers during friction depends on the property of
oil, called an oilness, the nature of which is still not sufficiently
clarified. These very thin layers of lubricant are very solidly
connected to the metal surfaces by adsorption forces.

B. V. Deryagin, investigating the condition of thin lubricating
layers, showed that oil under these conditions differs radically from
oil under volumetric conditions. The thin boundary films conduct
themselves like plastic bodies and they have a determined size of
shear stress. These investigations showed that the thin boundary
films possess a specific capacity of splitting action. The effect
of splitting is that pressure is developed in the thin boundary
layers which not only prevents the approach of the surfaces on which
the layer has been applied, but also tries to move them apart.
This pressure grows with a decrease in the clearance. The splitting
effect increases with speed, i.e., has not only a static, but also
a dynamic character, that is especially importantly because the

surfaces which possess relative movement are exposed to the lubricant.

A. S. Akhmatov considers the formation of boundary lubricating layers as one of the phenomena of crystallization. Boundary layers in the opinion of A. S. Akhmatov, are mono- or polycrystalline bodies, which appear because of the embryonic function of the primary layer. Lubricating materials in very thin layers under the two-sided effect of the surfaces of rubbing metals reveal exceptional anti-friction properties. The molecules of lubricating substances in the boundary layers provide sufficiently large strength for compression and easiness of shearing in a horizontal direction. This is explained by the small coefficient of friction during slipping of the lubricated surfaces. Thin lubricating layers can not only lower the force of friction to a considerable degree, but also exert a large effect on the amount of wear. Moreover, as the investigations of P. A. Rebinder, B. V. Deryagin, and others showed, in many instances a lubricant which rather intensively decreases the force of friction, and considerably increase wear.

P. A. Rebinder writes: "usually the matter is presented in such a manner so that a good lubricant always has as its purpose the averting of wear, along with a decrease in the coefficient of friction and the power being spent, i.e., the work spend in a unit of time on friction which turns into heat. This position proves to be incorrect; it is necessary to remember the dual role of a lubricant.

Studies showed that this dual role has a sufficiently defined theoretical explanation in that lubricating action is manifested always both on the external surface of metal, at the boundary of the metal with the surrounding medium, and inside the metal on its external layer. The active polar components of the lubricant, i.e., highest fatty acids, and organic compounds containing halogens and sulfur, facilitate a sharp increase in the capability for oils to penetrate a metal. The fact is that in the plastically deformed

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surface layer of metal micro- and ultramicro cracks appear between small crystals and in separate small crystals along the planes of slip. The lubricant penetrates these microscopic cracks more actively, the higher its oiliness. This internal effect of a lubricant always increases wear during boundary friction."

In connection with the great complexity of the processes taking place on the surfaces during boundary friction, up to now a universally recognized quantitative theory of boundary friction has not been created, however there is a large number of studies.

During the friction of metals their surface layers are heated to considerable temperatures. The amount of heat liberated during friction, depends upon the rate of slip, the load on the friction surfaces, the properties of the metals from which the parts are made, and the properties of the lubricant. With an increase in the rate of slip or the load the amount of heat given off in the process of friction increases - the temperature of the boundary film of oil rises. Upon achieving the critical temperature characteristic for every type of lubricant, the boundary film loses its lubricating capacity. A break in the boundary film occurs and the wear of the metals increases sharply. At constant values of loading and rate of slip, a similar regularity is obtained in the increase in the external temperature of testing, which is evident from Figs. 70 and 71.
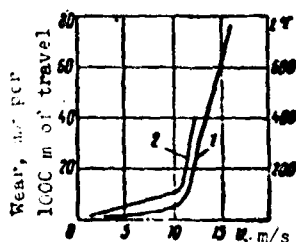
Fig. 70. Dependence of wear and the temperature of the surface of friction of steels on the rate of slip during boundary friction: 1 - wear; 2 - temperature.

Boundary lubrication during friction makes it possible, as a rule, to eliminate extremely undesirable wear from the gripping of metals, to shift its appearance to the side of very large rates of slip (Fig. 72).
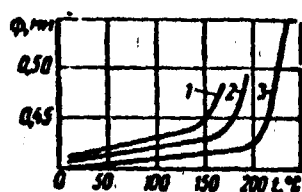
Fig. 71. Dependence of the diameter of a spot of wear on the temperature obtained during testing on a four-ball friction machine ($V = 0.4$ m/s $q - 31,500$ kgf/cm^2): 1 - MVS oil 2 - MSG oil; 3 - MKE oil.
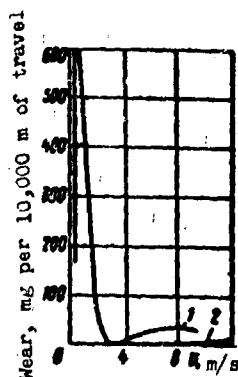
Fig. 72. Dependence of amount and character of wear of steel on the rate of slip: 1 - during dry friction; 2 - during friction with a lubricant.

The emergence and character of passage of the processes of sizing of metals depends on the nature of the oils. The oxidizing processes exert a large effect on boundary friction because products of the oxidation of hydrocarbon oils and the surface layers of metals substantially change the intensity of wear and the size of the coefficient of friction. Oxide layers play a most important protective role, averting intensive seizing of metals.

The seizing of metals during boundary friction can also be averted if protective layers of chemical compounds, different in their nature from oxide are formed on their surfaces. This can be layers of sulfides, chlorides, phosphides of metals, layers of the metallic soaps, and other substances. To obtain such protective layers various additives containing sulfur, chlorine, phosphorus, fatty acids, and others are out into oils.

The processes of friction and wear of metal surfaces under

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conditions of boundary lubrication depend very strongly on the gas medium of the friction zone. Studies of friction and wear of metals during steady boundary lubrication showed that in a gas medium not containing oxygen, gripping and the jamming of the metal surfaces occurs. In a gas medium containing oxygen, wear during boundary lubrication occurs without gripping and jamming.

In oils and lubricants with surface-active elements forming a boundary layer, there are polar molecules with a distinctly expressed assymetrical structure. The polar groups in a molecule are OH; COOH; NH_2, NO_2 or the atoms O, S, N, Cl, and others. The surface activity of the molecule depends on the size of its dipole moment which characterizes the asymmetry of the distribution of positive and negative electrical charges and a molecule and the relative size of the polar groups and of the nonpolar part of a molecule.

2. Operating Conditions of Aviation Lubricants

Aviation lubricants are subdivided into three basic groups:

lubricating oils, which under ordinary conditions are liquids;

consistent lubricants, which are plastic, greasy substances;

solid lubricants (graphite, molybdenum disulfide, mica, and others) used both in the form of components to oils and lubricants, and in the form of independent lubricants in assemblies where other lubricating materials are not practical.

Lubricating oils as a basic raw material are subdivided into petroleum, vegetable, animal, and synthetic.

With the development of aircraft engine construction thermal stresses, rates of motion, and the loads on the friction parts of engines rose. Oil in an engine undergoes the influence of high

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temperatures, the catalytic effect of different metals, large pressures, and the oxidizing effect of oxygen in the air. The operating conditions of oil change considerably depending on the type of engine and its structural pecularities. In certain cases to lubricate the same engine operating under different conditions (arctic or equatorial), different quality oils are necessary. For various types of aircraft engines, and also for aggregates and instruments primarily oil of a different viscosity is required. The viscosity is usually a basic determining indicator in classifying oils.

Oils are divided into the following types according to specific purposes:

oils for turbojet engines are low viscosity with a low thickening temperature;

oils for turboprop engines are low- and medium viscosity with a low thickening temperature and high lubricating capacity;

oils for piston engines are hignly viscous and subjected to deep cleaning;

oils for the reduction gears of helicopters (transmission) are high- and medium viscosity with good lubricating capacity;

aggregate and instrument oils are low viscosity and are subjected to deep cleaning, with a low thickening temperature.

3. General Requirements for Oils

Primarily oil should provide good lubrication of the friction parts and should avert their wear. It is advisable that, even during temporary breakdowns of the liquid state of a lubricant (in periods of starting, stopping, and others) oil should shield well the friction parts from wear. Oil under any conditions of operation should be

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reliably supplied to friction parts and to those parts of an engine, unit, or instrument being cooled.

During prolonged operation oil should retain its properties and not form deposits on parts because deposits facilitate overheating and soiling of an engine, unit, or instrument. Oil should not cause the corrosion of parts, it should itself shield the part from corrosion. It is necessary that oils have a low cost. One of the most important requirements for oils is their non-toxicity and low flammability.

On the strength of these general requirements, it is advisable that oils have the following properties:

the lowest possible, but sufficient viscosity to create a reliable liquid layer in spaces at a maximum operating temperature;

a sharp growth in viscosity with an increase in pressure;

a gently sloping viscosity-temperature characteristic;

a low thickening temperature;

good lubricating capacity;

an absence of unstable component parts, which separate out in the form of deposits in the engine;

an absence of corrosion active impurities and chemically unstable component parts which are inclined to be transformed into corrosion active substances,

a high flash temperature;

physical homogeneity (an absence of mechanical impurities and water).

Oils which completely satisfy all the named requirements practically cannot be obtained because a number of the requirements contradict each other. Therefore the selection of an oil for a specific engine is accomplished so that according to its basic indicators it would most fully correspond to the requirements for this engine.

C H A P T E R   IX

BASIC INFORMATION ON THE PRODUCTION OF OILS

1.   Obtaining Petroleum Oils

Mazuts - the residue from the direct distillation of petroleum, serve as the basic raw material for obtaining oils. The basic method of processing mazut into lubricating oils is fractional distillation. In this case low viscosity lubricating oils having the general name distilled are obtained from the low-boiling fractions of mazut.

After the oil distillates are removed from the mazut tar or with a less deep selection of the oil fractions flux oil is obtained from the residue. Tars and flux oils of butyric petroleum are used to get highly viscous residual oils.

Mazuts boil away over a wide range of temperatures, moreover the boiling point at atmospheric pressure of a majority of the oil fractions is higher than their splitting (cracking) temperature. Therefore fractional distillation of a mazut is accomplished in a vacuum in the presence of water vapor.

The first Soviet vacuum tubular device was constructed in Baku in 1928 for the distillation of butyric tar. During the subsequent years vacuum tubular devices for the distillation of mazuts became widely distributed.

Figure 73 shows a diagram of the vacuum device. Mazut is pumped through heat exchangers 9 and 11 by the raw material pump, is heated in them due to the heat of the outgoing distillates and tar and then is pumped through tubular furnace 4, from where at a temperature of 420°C it enters fractionating column 3. Here the mazut is divided into separate fractions - oil distillates of different viscosity. From the bottom of the column flux oil or tar is removed. The mazut is heated in vacuum tubular devices without decomposition to 425°C. This is achieved because of the short length of time the mazut is in the tubular furnaces and under a vacuum of 250-300 mm Hg, under which the devices operate.
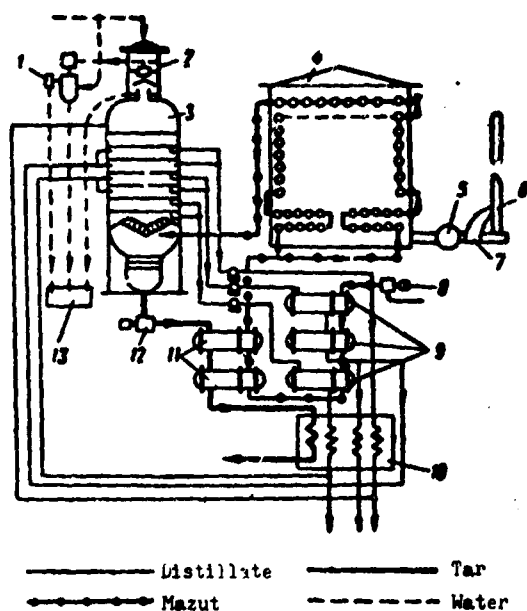
Fig. 73. Diagram of a vacuum device: 1 - ejector; 2 - barometric condensor; 3 - fractionating column; 4 - furnace; 5 - fan; 6 - smoke stack; 7 - air heater; 8 - raw materials pump; 9 - distillation heat exchangers; 10 - refrigerator; 11 - mazut heat exchangers; 12 - pump; 13 - well.

———— Distillate   ———— Tar
—•—•—•— Mazut   —— —— —— Water

With an increase in temperature of heating and vaporization of the mazut (under conditions which prevent the possibility of decomposition) the depth of the removal of petroleum distillates from it increases.

2. Cleaning of Oils

The petroleum distillates and residues obtained by distilling mazut consist of a mixture of various classes of hydrocarbons and contain oxygen, sulfurous, and nitride compounds.

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Oil distillates and residue are half-finished products. In order to obtain finished oils, it is necessary to rid these half-finished products of harmful impurities. The simplest means of cleansing oil distillates is leaching, i.e., treatment with an alkali solution to remove petroleum acids.

Acid-alkali cleansing gives better results; this is treating the oil half-finished product with strong sulphuric acid (96-98%), and then with alkali. Asphalt-resinous substances, a part of naphthenic acids, and heavy aromatic hydrocarbons easily enter into a reaction with sulphuric acid and are removed from the oil. Then half-finished products are processed with sodium alkali, which neutralizes the organic acids and the residues of sulphuric acid. To remove the residue of alkali and salts, the oil is washed with water and dried with heated air. Cleansing of many distilled oils is accomplished by the acid-alkali method.

During washing of the oil with water after neutralization of it with the alkali solution, stable, difficultly destroyed emulsions can be formed, and also hydrolysis of the salts (soaps) formed occurs. Therefore when cleaning oils (especially relatively highly viscous) neutralization of the acid oil with alkali is often substituted by treatment with bleaching clays. In this case oil is mixed up with finely ground bleaching clay. Upon contact with the hot oil the clay adsorbs on its surface the asphalt-resinous substances, the residues of sulfuric acid, and acid tar. After this the clay is separated out with the aid of filters. The cleaning of oil with treatment by sulphuric acid and bleaching clay by means of a contact filtration bears the name acid-contact cleaning.

In processing mazuts containing a considerable quantity of polycyclic hydrocarbons with a large number of ring and short aliphatic chains in the molecules which are easily oxidized and which worsen the viscosity-temperature properties of oils, the methods of cleaning examined above prove to be insufficiently satisfactory.

Therefore with an increase in the consumption of lubricating oils and
the need to process mazuts not only of selected butyric oil, but also
of less qualitative types, selective cleaning was expanded, i.e.,
cleaning with the aid of selective solvents. This the method of
cleaning is based on the selection of solvents possessing at a
determined temperature and ratio of the amount of solvent and oil
being purified a different dissolving capacity for the undesirable
and the useful components of oil.

When the mixture of oil and solvent settles it is divided into
a layer of oil from which the undesirable components have been
removed, and an extract layer, which is a solution of the components
(extracts) separated from oil in the solvent.

These layers are separated from one another and the solvent is
driven off from them in order to use it again to clean the next
portions of oil.

After selective cleaning, and sometimes also before it an ad-
ditional contact or acid-contact cleaning of the oil is accomplished.
Furfurole, phenol, nitrobenzine, and others are used as selective
solvents

Furfurole $C_5H_4O_2$ has the following structure:

$$HC - CH$$
$$\| \quad \| \quad O$$
$$HC \quad C - C \diagdown$$
$$\diagdown / \quad H$$
$$O$$
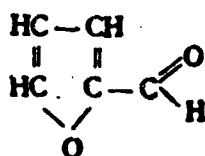
It possesses good selective properties, but a limited dissolving
capacity, in consequence of which it is used in a relatively large
quantity (up to 150-400%) to the oil being purified.

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Furfurole is a colorless liquid with the pleasant smell of bread, is poisonous, density at 25°C - 1.155, boiling point 161.7°C.

Phenol C_6H_5OH has the following structure:

$$
\begin{array}{c}
OH \\
| \\
C \\
/ \; \backslash\!\backslash \\
HC \qquad CH \\
|\qquad\qquad | \\
HC \qquad CH \\
\backslash\!\backslash \; / \\
CH
\end{array}
$$
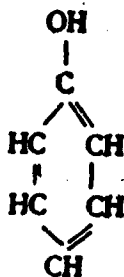
Phenol is a colorless crystalline substance with a melting point of 40.9°C and boiling point of 181.75°C. The density of phenol at 41°C equals 1.05. Phenol has a characteristic smell, possesses a somewhat lower selectivity then furfurole, but has a good dissolving capacity. With phenol cleaning the content of sulfur in the oil decreases considerably (30-50%).

Nitrobenzine $C_6H_5NO_2$ belongs to a number of effective selective solvents and is distinguished by high toxicity. The boiling point of it is 211°C, melting - 5.76°C, density at 15°C - 1.2.

To get the high-quality viscous light oils of the residual type cleaning with paired solvents is used in which are selectively dissolves the components subjected to removal, and the other - the useful components of oil.

Very good cleaning is provided in this manner. Technical cresol $C_6H_4-CN_2-OH$ (a mixture mainly of *m*-cresol and *n*-cresol) is used as a solvent in this case.

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m—cresol OH OH *n*—cresol
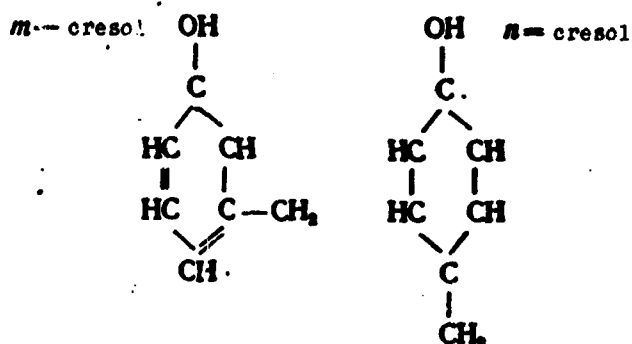
In particular, a mixture of cresols with 30-50% phenol and technical propane C_3H_8 is used. The process is accomplished under elevated pressure (up to 20 kgf/cm^2). Oil is cleaned as far as possible with bleaching clay.

If there is very much resinous-asphalt substances in an oil half-finished product, their removal by the above methods is complex and uneconomical in connection with the large expenditure of sulfuric acid and solvents. In these cases preliminary deasphalting of the oil half-finished product is accomplished. Upon dissolving the oil half-finished product in gasoline or liquid propane the semisoluble resinous-asphalt substances in it fall out in a sediment. After e removal of the deposit the solvent is driven off from the oil.

To get oils with a low temperature of thickening from paraffinaceous oils after cleaning the oil is subjected to deparaffination — the removal of the high-melting paraffin hydrocarbons from it. The oil is dissolved in ligroin, liquid propane, or in any other low-freezing solvent. The solution is cooled to a temperature of minus 25-40°C (depending on the required thickening temperature of the oil) and is fed to high-speed centrifuges, where the thickened hydrocarbons under the influence of centrifugal forces are separated from the oil. A mixture of solid paraffins with a certain amount of liquid oil and of admixtures, called petrolatum, is used to get a solid white paraffin and ceresin.

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3. The Chemical Composition of Oils

Unlike fuels oils consist of hydrocarbons of a considerably greater molecular weight. These hydrocarbons possess a more complex structure and they differ in the abundance of isomeric forms, that extremely hinder the possibility of isolating individual hydrocarbons and, therefore, their study.

The basic groups of hydrocarbons in the composition of lubricating oils are: paraffin (alkanes), naphthenic (cyclanes), aromatic, and naphthene-aromatic, in the molecules of which are simultaneously both naphthenic and aromatic rings. Paraffin hydrocarbons are present in all oils. In most cases the content of paraffin hydrocarbons decreases with an increase in the boiling point of fractions, but sometimes a relatively small content of them in butyric fractions is noted along with an increase of them in the distillation residues (flux oils and tars).

The hydrocarbon n-heptadecane $C_{17}H_{26}$ and the more high-molecular n-paraffins under ordinary conditions are solid substances present in oils in a dissolved or solid (crystalline) form. The solid hydrocarbons of oil are subdivided into paraffins, which possess a macrocrystalline structure (ribbon or lamellar), and ceresins, which possess a fine crystalline (needle-shaped) structure. Of the paraffins, the cresins differ in greater density and higher boiling points melting temperatures at the same molecular weights. Furthermore, the ceresins are more reactionable.

Solid napthenes and solid aromatic hydrocarbons are present in the ceresins frequently in a mixture with the solid high-melting paraffins.

The presence of paraffins in a liquid phase causes a lower viscosity of the butyric fractions of oil and good viscosity-temperature properties. In this case for n-paraffins these properties are

manifested more distinctly than in the isoparaffins.

Presence of high-molecular paraffins in the oils leads to an increase in the thickening temperature, a loss of fluidity with a decrease in temperature as a result of the appearance of the crystalline phase and of structure formation.

In the butyric fractions of oil mono- and the polycyclic hydrocarbons are found in large quantities - naphthenes with five- and six member rings in the molecules, and also aromatic and naphthene-aromatic hydrocarbons.

Naphthenes are present in the liquid and solid (crystallic) phases, in the composition of ceresin. Naphthenes with a long lateral alkyl group of normal structure are most easily crystallized. In the presence of a branch lateral chain or of several lateral chairs of a shorter length instead of one long chain the melting temperature of naphthenes falls considerably. But at the same time naphthenes whose molecules have several lateral chains with the same number of carbon atoms in them instead of one long lateral chain in a cyclic nucleus possess considerably greater viscosity and worse viscosity-temperature properties. The presence and sizes of the lateral chains for other cyclic hydrocarbons - aromatic and naphthene-aromatic also exert a similar effect on the viscous properties.
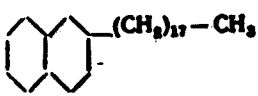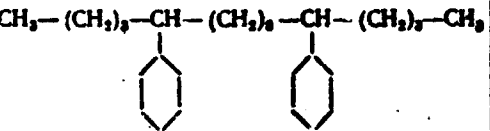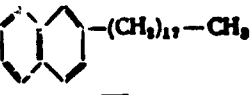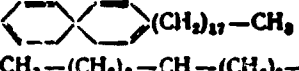
In this case for all alkyl substituted cyclic hydrocarbons an increase in viscosity is characteristic with a simultaneous deterioration of the viscosity-temperature properties with an increase in the ratio of the number of carbon atoms found in the cyclic part of a molecule, to the number of carbon atoms in the lateral chains.

The viscosity-temperature properties of cyclic hydrocarbons in the presence of three and more rings in a molecule are especially worsened. With one and the same number of rings in a molecule the

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viscosity-temperature properties improve with an increase in the length and a decrease in branching of the lateral circuits.

Not only the number, but also the position of the rings in molecules has an effect on the viscous properties of polycyclic hydrocarbons. Thus, the comparison of naphthenes and aromatic hydrocarbons with a different location of rings with the same number of carbon atoms in the lateral chains (C_{18}) given in Table 32, shows, that when the rings in the molecules are located farther and farther from one another, the viscosity of the hydrocarbons increases, and the viscosity-temperature properties worsen.

Table 32. Viscosity properties of bicyclic hydrocarbons with 18 carbon atoms of the lateral chains.

Empirical formula	Structure	Kinematic viscosity oSt	Indicator of the viscosity-temperature properties
	Naphthenes		
$C_{28}H_{54}$	⬡⬡—(CH$_2$)$_{17}$—CH$_3$	30,80	100,0
$C_{30}H_{58}$	CH$_3$—(CH$_2$)$_3$—CH—(CH$_2$)$_8$—CH—(CH$_2$)$_3$—CH$_3$ (rings)	51,28	61,1
	Aromatic hydrocarbons		
$C_{28}H_{44}$	⬡⬡—(CH$_2$)$_{17}$—CH$_3$	22,86	100,0
$C_{28}H_{46}$	⬡⬡—(CH$_2$)$_{17}$—CH$_3$	29,18	93,6
$C_{30}H_{46}$	CH$_3$—(CH$_2$)$_3$—CH—(CH$_2$)$_8$—CH—(CH$_2$)$_3$—CH$_3$ (rings)	33,38	65,7

The oxidation and gumming of oils has been most fully investigated by N. I. Chernoznukov and S. E. Kreyn. The primary products of the oxidation of a majority of hydrocarbons are peroxide compounds:

monoalkyl peroxide (hydrogen peroxide) R—OO—H, dialkyl peroxide
R—OO—R, oxyalkyl peroxide R—OO—CH$_2$—OH, dioxyalkyl peroxide

$$HO—CH—OO—CH—OH$$
$$\quad\quad |\quad\quad\quad\quad |$$
$$\quad\quad R\quad\quad\quad\quad R$$
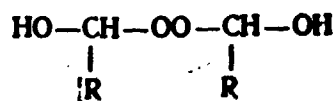
and more complex peroxide compounds. Further oxidation and oxidizing
polymerization of the hydrocarbons can go in two basic directions:
with the formation of acid products and neutral products according
to the system:

                             acids—hydroxy acids—complex esters—acid resins

Hydrocarbons   (asphaltogenic acids)

                             resins—asphaltenes—carbenes—carboids
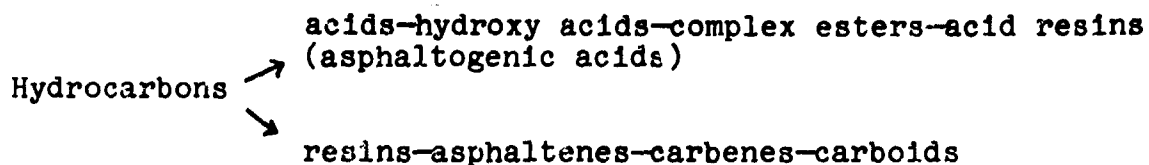
The capacity of lubricating oils to be oxidized and form tar
depends on the structure of the molecules, their hydrocarbon composi-
tion and the conditions of oxidation. N. I. Chernozhukov and S. E.
Kueyn establisned that the naphthenes found in oils, can be oxidized
by the oxygen in the air at elevated temperatures. The capacity
cf naphthenes to be oxidized increases with an increase in their
molecular weight and in the presence of short lateral chains. The
more ring contained in the molecules of naphthene, the more products
of oxidation obtained. The basic products of the oxidation of
naphthenes are acids and hydroxy acids.

Aromatic hydrocarbons oxidize somewhat more difficulty than
naphthenes, but their resistance to oxidation falls in proportion
to the complexity of the molecules, especially, with an increase in
the number of rings. In addition in the case of the presence in
aromatic rings of short lateral chains (or short chains which connect

aromatic radicals between themselves oxidation is accompanied by the formation of high-molecular products - resins, asphaltenes, and carbenes, frequently falling out in a sediment. If even in aromatic rings there are long alkyl chains, then as a result of oxidation less polymers are formed but more organic acids and similar products, which do not fall out in a sediment.

Aromatic hydrocarbons in mixtures with naphthenes protect the latter from oxidation. Naphthene-aromatic hydrocarbons react easily with oxygen with the formation of acids, hydroxy acids, resinous substances, and asphaltenes, karbenes, etc., which can fall out in a sediment.

The amount of these or those products of oxidation is determined by the prevalence of naphthenic or aromatic rings in the molecules. To get oils which do not give deposits upon oxidation it is advisable that the naphthenic and aromatic hydrocarbons with a small number of rings and long paraffin chains in the molecules remain in them. Polycyclic hydrocarbons with a large number of rings and short chains should be removed when cleaning the oils.

C H A P T E R   X

SYNTHETIC LUBRICANTS

Petroleum lubricants already at the modern level of the development of technology far from satisfy the requirements presented to them over a wide range of operating conditions. The mineral oils of even better quality have substantial deficiencies: poor viscosity-temperature characteristics and low stability at high temperatures and pressures.

If one considers that the further development of technology will be associated primarily with an increase in the speeds of movement, specific loads on machine parts, and with an increase in the operating temperatures, then it is entirely obvious that petroleum lubricating materials will be completely unfit for these conditions. In recent years more and more attention has been given to the search for and study of lubricating materials new in their nature and properties.

Of the large number of synthesized and studied chemical compounds greatest interest is given to four classes of synthetic nonhydro-carbon oils: based on complex esters, polyalkylene glycol, poly-siloxane, fluorocarbon, and chlorofluorocarbon.

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1. Oils Based on Complex Esters

Esters are obtained during the interaction of acids and alcohols:

$$R-C\underset{OH}{\overset{O}{\diagup}} + H-O-R' \rightleftarrows R-C\underset{O-R'}{\overset{O}{\diagup}} + H_2O.$$
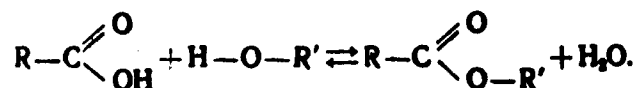
Such reactions are called esterification reactions. The process of exterification is reversible. A reaction between an ester and water where acid and alcohol is obtained is called saponfication.

Two molecules of alcohol can also form a molecule of ester, liberating a molecule of water:

$$R-OH + OH-R' \rightarrow R-O-R' + H_2O.$$
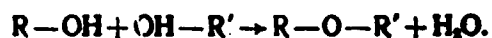
In the first case complex esters are obtained, in the second - a simple ester.

Alcohols contain the hydroxyl group OH, connected with a hydro-carbon radical·R. As a result of substitution in the hydrocarbons of two or more atoms of hydrogen by a hydroxyl group diatomic or poly-atomic alcohols are obtained. Usually monatomic alcohols are called alcohol, diatomic - glycols, triatomic - glycerines.

The carboxylic acids in the composition of complex esters are organic acids containing a univalent carboxyl group

$$-C\underset{OH}{\overset{O}{\diagup}}$$

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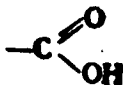
connected with the hydrocarbon radical. According to the number of carboxyls in a molecule carboxylic acids are single-base and polybasic having two and more carboxyl groups.

With the interaction of monatomic alcohols and of single-base acids simple monoesters are formed. With the interaction of dibasic acids with monatomic alcohols or diatomic alcohols with single-base acids double complex esters called diesters are formed.

Monoesters have a relatively high thickening temperature and a steep viscosity-temperature characteristic. They have an inadequate stability, in connection with which monoesters are less promising as a base for lubricating oils.

The complex esters and specifically, diesters, possess considerably better properties. The structure and properties of some complex esters are given in Table 33.

The important advantage of diesters is their capability to synthesize compounds of a high molecular weight with a low volatility from available aliphatic alcohols and acids with a low molecular weight. The presence in such compounds of two reactionable groups makes it possible to obtain compounds of a different structure and properties depending on the operating requirements. Up to the present time tens of thousands of various diesters have been obtained and investigated, many of which can serve as a base for high-quality oils.

The properties of the diesters depend upon their chemical structure. With an increase in the length of a hydrocarbon chain the viscosity and thickening temperature rise and the angle of slope of the viscosity-temperature curve decreases. Cyclic groups cause a considerable increase in viscosity, but worsen the viscosity-temperature characteristics of the diesters. Diesters of an isomeric

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structure receive the widest distribution as lubricating oils.

Table 33. Characteristics of some complex esters.

Name and the structure of esters	Density	Viscosity cSt		Temperature °C	
		20°C	99°C	of thickening	Flash
Dioctyl ester of adipic acid $CH_2-CH_2-COO-C_8H_{17}$ | $CH_2-CH_2-COO-C_8H_{17}$	0,919	14,8	2,85	4	215
Dioctyl ester of λ-methyladipic acid CH_3 | $CH_2-CH-COO-C_8H_{17}$ | $CH_2-CH_2-COO-C_8H_{17}$	0,927	16,8	2,66	—32	205
Di-2 ethylhexyl ester of adipic acid C_2H_5 | $CH_2-CH_2-COO-CH_2-CH-(CH_2)_3-CH_3$ | $CH_2-CH_2-COO-CH_2-CH-(CH_2)_3-CH_3$ | C_2H_5	0,925	12,8	2,26	—78	215
Di-2 ethylhexyl ester of sebacic acid C_2H_5 | $CH_3-(CH_2)_3-COO-CH_2-CH-(CH_2)_3-CH_3$ | $CH_3-(CH_2)_3-COO-CH_2-CH-(CH_2)_3-CH_3$ | C_2H_5	0,912	23,2	3,30	—72	225
Di-2 - ethylhexyl ester of phthalic acid C_2H_5 | $C_6H_4\diagdown^{COO-CH_2-CH-(CH_2)_3-CH_3}_{COO-CH_2-CH-(CH_2)_3-CH_3}$ | C_2H_5	0,990	121,0	5,04	—42	178

Based on diesters we obtain lubricating oils, which possess higher indices of viscosity, lower thickening temperatures, less volatility (Fig. 74), and less flammability, than petroleum oils. The lubricating properties, resistance of the diesters to the effect

of oxygen and heat is approximately the same as in petroleum oils.
On the effect on products of oil resistant rubber diesters show a
worst effect because they cause swelling and the softening of rubber
gaskets, hoses, and other parts to a greater degree than petroleum
oils.
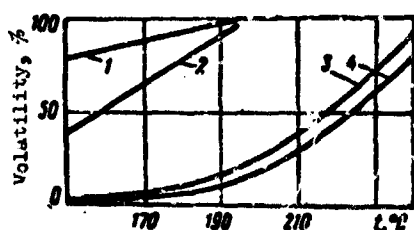
Fig. 74. Dependence of the
volatility on the temperature of
syntnetic and petroleum oils; 1,
2 - petroleum oils; 3, 4 - syn-
thetic oils based on diesters.

Synthetic oils based on diesters are used today in a pure form
and in mixtures with petroleum oils for lubricating turbojet engines
(in USA, England), various mechanisms, apparatuses, and instruments.
Diester oils are especially good for lubricating friction nodes
operating at small loads but over a wide range of temperatures (from
120 to -65°C). Diester oils can be used as liquids for hydraulic
systems. To improve the properties of synthetic diester oils various
additives (viscosity, antiwear, etc) are added to them.

2. Polyalkylene Glycol Oils

Polyalkylene glycols (polyglycols) are obtained by interacting
various glycols and other alcohols with ethylene oxide, propylene
oxide, or with their mixtures and are according to structure simple
polyesters with the long chains, whose molecules can contain one or
several free hydroxyl groups. Generally, the formula for polyethylene
glycols has the following form:

$$OH-CH_2(CH_2-O-CH_2)_n-CH_2-OH.$$
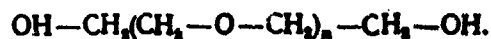
At $n = 1$ the polymer has a composition

$$OH-CH_2-CH_2-O-CH_2-CH_2-OH$$
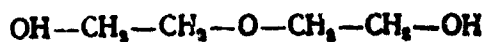
and is called diethylene glycol.

At $n = 2$ triethylene glycol is obtained

$$HO-CH_2-(CH_2-O-CH_2)_2-CH_2-OH.$$
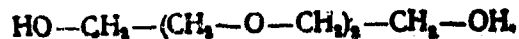
The reaction for obtaining polyethylene glycols takes place according to the following system:

$$H_2C-CH_2+H_2O \rightarrow HO-CH_2-CH_2-OH,$$
$$\overset{\diagdown \diagup}{O}$$
$$HO-CH_2-CH_2-OH+H_2C-CH_2 \rightarrow HO-CH_2-CH_2-O -$$
$$\overset{\diagdown \diagup}{O}$$
$$-CH_2-CH_2-OH.$$
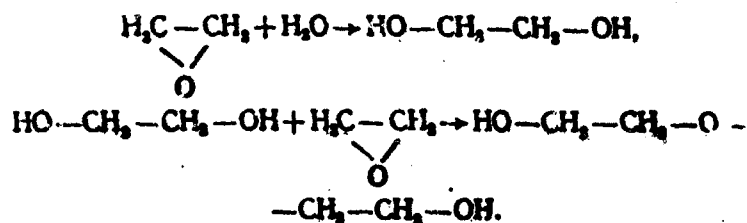
It is possible to obtain the most varied polyglycols depending on the basic alcohols and hydrocarbon oxides used in the reaction and on the conditions of carrying out the process.

Polyglycols mix up in all ratios with water and are insoluble in hydrocarbons.

If a polyglycol hydroxyl group is substituted for an alkyl ester group, we will get polyglycol esters. Esterification of polyglycols makes it possible to introduce radicals varied in amount and structure into the glycol moledules and in this way to change the properties

of the obtained products to the desirable side. The esterification
of the final hydroxyl groups of a polyclycol can be transferred into
compounds which dissolve well in petroleum hydrocarbons and are
practically insoluble in water. Today polyglycols that are soluble
and insoluble in water are produced.

Depending on the length of the molecular chain and the structure
of the polyglycols their viscosity can change over wide limits from
6-8 to 10,000 cSt and more at 50°C. Polyglycol oils are distinguished
from petroleum oils by their better antiwear properties, low
thickening temperature, (from 55 to -65°C), high viscosity indices
(within the limits 135-180), and low volatility. Polyglycol oils
do not form resinous compounds at elevated temperatures in the presence
of oxygen and air; they withstand high temperatures (to 300°C) and
do not corrode metals or cause the swelling or softening of synthetic
and natural rubber. They ignite with a greater difficulty than
petroleum oils. Table 34 gives the properties of oils based on
polglycols, and in Fig. 75 - their viscosity-temperature curves.
In this figure for comparison the viscosity-temperature curves of
mineral oils MK-8 and turbine MK-22 have been plotted. From the
figure it is evident that polyglycol oils have a more gently sloping
viscosity-temperature curve than do the mineral oils of equal
viscosity.

Table 34. Properties of synthetic polyglycol
oils.

Indicators	Arbitrary designation of the type of oil		
	I	II	III
Density	0,951	0,960	0,970
Viscosity, cSt, at a temperature of °C:			
100	3,2	5,3	6,5
50	8,5	15,1	20
0	15	100	151
—40	1950	4860	13000
Index of viscosity	162	180	107
Temperature of thickening, °C	—55	—55	—55
» Flash, °C	198	215	251
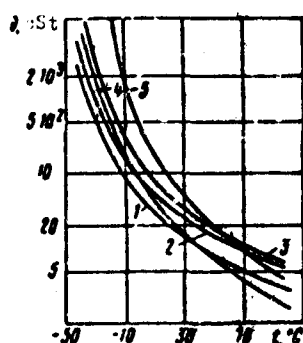
Fig. 75. Viscosity-temperature
curves of polyglycols and mineral
oils: 1, 2, 3 - polyglycol oils;
4 - MK-8 oil; 5 - MK-22 turbine
oil.

Polyglycol oils can be used in various areas of technology: for
lubricating turbojet engines, as transmission oils, for work at
high loads and temperatures, as compressor oils, as the liquid in
hydraulic systems, etc.

Polyglycols are added to petroleum oils to improve their anti-
wear properties, and are also used as bases during the manufacture of
consistent greases. Greases based on polyglycols are characterized
by high thermal and colloidal stability and by good low-temperature
properties. The production of synthetic lubricating oils based on
polyglycol compounds has sufficient raw material resources. The
unsaturated gaseous hydrocarbons (ethylene and propylene), which can
be obtained from natural hydrocarbon gas and the industrial gases
of oil-refining plants serve as the base products.

3. Oil Based on Silicon Organic Compounds

Recently polymer silicon organic compounds, called polysiloxanes
or silicones have received a greater and greater distribution as
special lubricating oils and liquids.

Unlike natural petroleum oils consisting of hydrocarbons -
compounds, in which a molecular chain has been formed from carbon

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atoms - polysiloxanes have in their base a chain of alternating atoms of silicon Si and oxygen O, the so-called siloxane grouping

$$-\overset{\displaystyle |}{\underset{\displaystyle |}{Si}}-O-\overset{\displaystyle |}{\underset{\displaystyle |}{Si}}-O-\overset{\displaystyle |}{\underset{\displaystyle |}{Si}}-$$
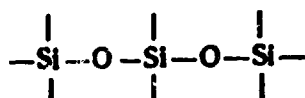
Hydrocarbon and other organic radicals of a different structure are joined to the atoms of silicon in the form of lateral chains. Depending on the length of the molecular chains, the structure and the composition of the lateral chains of polysiloxanes have varied physical and chemical properties.

The distinctive properties of many silicon organic products are their resistance to high temperatures and oxidation, resistivity to the effect of moisture, and good viscosity-temperature properties. Silicon organic compounds occupy first place among other synthetic liquids according to the viscosity-temperature characteristic, which is evident from Fig. 76.
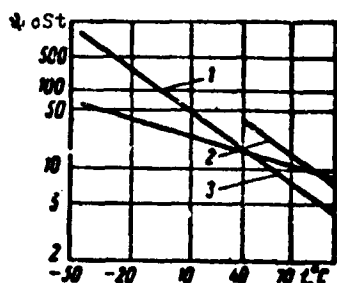
Fig. 76. Viscosity-temperature curves of oils: 1 - dimethyl silicon; 2 - mineral; 3 - a derivative of polyglycol.

The good heat resistance of silicon organic compounds makes it possible to use them as a heat-conductor under conditions of prolonged operation at 350°C.

Silicon organic compounds can be the base for obtaining synthetic lubricating oils capable of operating at the high temperatures characteristic of powerful jet engines.

Polymers with methyl and ethyl have a practical value as lubricating oils and liquids. The first answer the general formula

$$\left[\begin{array}{c} CH_3 \\ | \\ -Si-O- \\ | \\ CH_3 \end{array} \right]_n$$
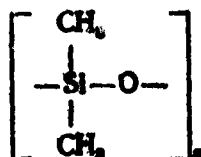
and are called methyl polysiloxanes or methyl silicones, the second answer the general formula

$$\left[\begin{array}{c} C_2H_5 \\ | \\ -Si-O- \\ | \\ C_2H_5 \end{array} \right]_n$$
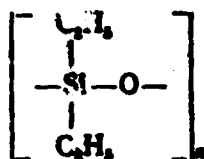
and are called ethyl polyxiloxanes or ethyl silicones. Also known are the phenyl polysiloxane compounds, containing in the lateral chain phenyl radicals, combined alkylaryl polysiloxanes, for example methylphenyl-, ethylphenyl polysiloxanes, and other silicon organic polymer products. Great work in the investigation of polysiloxanes has been accomplished by the scientists K. A. Andrianov, B. N. Dolgov, M. M. Kotonadi, and A. P. Kreshkov. They discovered a number of the very valuable and unique properties of polysiloxanes and other silicon organic compounds.

Polysiloxanes are colorless transparent oily liquids of different degrees of viscosity. They dissolve well in hydrocarbons,

haloid hydrocarbons, and do not dissolve in water, alcohols and other polar solvents.

The properties of polysiloxanes to a considerable degree are determined by the properties of the siloxane grouping. The bond of silicon with oxygen is distinguished by its greater thermal stability than the organic polymers which is determined by the greater energy of formation of the bond. Thus, the energy of the Si—O bond equals 89 kcal/mole, and the energy of the C—C bond equals 58.6 kcal/mole. The energy of the Si—C bond (57 kcal/mole) is closed to the energy of the C—C bond.

The thermal destruction of polysiloxanes is associated mainly with splitting the lateral organic radicals, moreover the basic polymer siloxane chain is not destroyed. K. A. Andrianov proved, that oxidation of the organic radical will entail the formation of oxygen bridges between the molecules of the polymers, which hamper the access of oxygen to the other organic radicals which slows down the further oxidation of the polymer.

Polysiloxanes are distinguished by their great chemical inertness which is also explained by the stability of the Si—O bond. Many aggressive reagents (nitric acid, sulfuric acid, and others) do not act on them. Polysiloxane oils practically do not corrode steel, cast iron, copper, brass, aluminum, lead, bronze, magnesium, tin, and other metals even with heating to 150°C.

The very low thickening temperature of polysiloxanes and the small dependence of viscosity on the temperature is explained by the small polarity of these compounds, and, therefore, by the small forces of intermolecular interaction, which is considerably less than even such a molecular polymer as polyisobutylene.

Figure 77 compares the viscosity of paraffin hydrocarbons of a normal structure and methyl polysiloxanes with an open chain.

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Polysiloxane oils, even the low viscosity types have a relatively
high molecular weight and, therefore, high boiling and flash
temperatures.
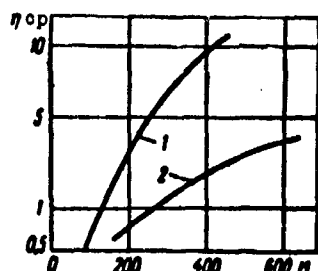
Fig. 77. Dependence of the
viscosity on the molecular weight:
1 - n-paraffin hydrocarbons; 2 -
methyl polysiloxanes with an open
chain.

The considerable mechanical strength of the Si—O bond causes the
high resistivity to mechanical failure of polysiloxanes during opera-
tion under large loads and at high rates of shift.

The chemical inertness and weak polarity of polysiloxanes causes
their poor antiwear properties during boundary friction. The anti-
wear properties of the oils can be determined on a four-ball machine,
a diagram of the friction node of which is shown in Fig. 78.
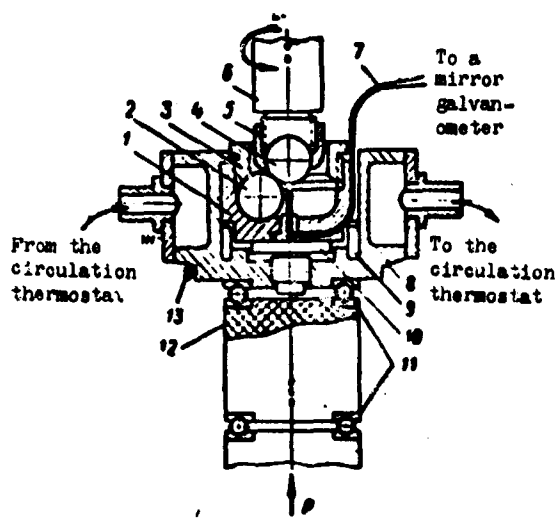
Fig. 78. Diagram of the friction node of a four-ball machine: 1 -
cup; 2 - lower ball; 3 - nut; 4 - upper ball; 5 - the shaft nut;
6 - shaft; 7 - thermocouple; 8 - thermostat housing; 9 - pin; 10 -
plate; 11 - fixed bearings; 12 - textolite support; 13 - cable.

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Polysil ..anes according to their antiwear properties are inferior to mineral oils which is evident from Fig. 79. Weak anti-wear properties are one of the main deficiencies of polysiloxanes as lubricating oils.
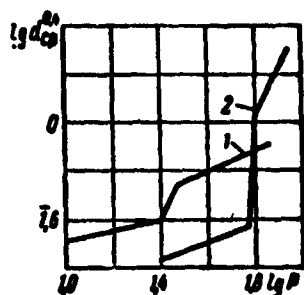
Fig. 79. Dependence of wear on the load, obtained on a four-ball machine: 1 - ethyl polysiloxane; 2 - MS-20 oil.

Methyl-, ethyl-, methylphenyl, and ethylphenyl polysiloxanes have the greatest practical application today as lubricating oils and liquids. Polysiloxanes are usually used where high chemical and thermal stability and good viscosity-temperature characteristics are required, and there are no high requirements for the greasing capacity of the oil. Polysiloxanes in a mixture with mineral oils and in a pure form are used to transfer pressure in various hydraulic systems as working liquids for hydraulic shock absorbers.

They are also used for the manufacture of consistent greases and instrument oils.

4. Fluorocarbon Oils

The introduction of fluorine into the molecules of organic compounds has a very strong effect on their physicochemical properties. By the fluorination of hydrocarbons compounds are obtained in which the hydrogen atoms are substituted by fluorine:

```
 F   F   F   F   F   F   F
 |   |   |   |   |   |   |
—C—C—C—C—C—C—C—...
 |   |   |   |   |   |   |
 F   F   F   F   F   F   F
```
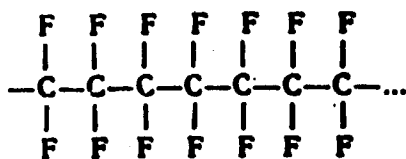
With the complete substitution of all hydrogen atoms the
hydrocarbons turn into fluorocarbons. In this case an attachment
"perfluoro" is added to the name of a completely fluorinated hydro-
carbon.

Fluorocarbon oils can consist of completely fluorinated paraffin,
naphthenic, aromatic hydrocarbons or combined type hydrocarbons
with lateral chains and cycles.

Fluorine is the first element of the group of haloids. It
is extremely reactionable and in this respect considerably exceeds
its analogs: chlorine and iodine. The direct fluorination of hydro-
carbons is very vigorous and is accompanied by an explosion. Today
rather convenient methods of synthesizing fluorocarbons have been
developed.

Perfluorocarbon oils from an external view are transparent
liquids of varying viscosity. They dissolve well in petroleum-
ether ester, ethyl ester, chlorinated hydrocarbons, and do not
dissolve in hydrocarbons, alcohols, and water.

Perfluorocarbons are distinguished in physicochemical proper-
ties in a number of characteristics and primarily by an extremely high
chemical and thermal stability. They do not interact at room
temperature with such strong oxidizers as nitric acid, concentrated
sulfuric acid, chromic acid, and others. They do not interact with
sodium up to a temperature of 350°C. Fluorocarbons are stable to the
interaction of oxygen, they do not burn and they do not decompose
up to temperatures of 400-500°C. The thermal stability of

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fluorocarbons is higher, than that of the polysiloxanes. The high
thermal resistance and chemical inertness of fluorocarbons are
explained by the greater strength of the bond of carbon with fluorine,
than of carbon with hydrogen.

Fluorocarbon oils have very steep viscosity-temperature curve.
According to the viscosity-temperature characteristic they are
inferior to even mineral oils (Fig. 80). The density of fluorocarbons
is 2-3 times higher than the density of corresponding hydrocarbons.
Fluorocarbons have a higher melting temperature than hydrocarbons
of the same structure. Fluorocarbon oils possess rather good anti-
wear properties, in many instances not inferior to the antiwear pro-
perties of mineral oils.
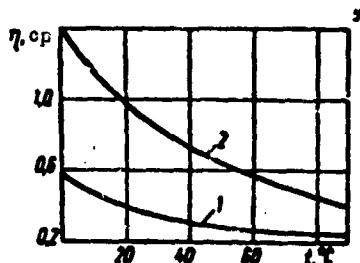
Fig. 80. Dependence of the vis-
cosity of perfluorocarbons and
hydrocarbons on the temperature:
1 - n-heptane; 2 - perfluorine;
— n-heptane.

The high thermal and chemical stability of fluorocarbon oils is
used when it is necessary to provide lubrication for friction nodes
that operate at high temperatures in an atmosphere of chemically
active substances. Fluorocarbon oils are used as a base for preparing
thermal and chemically stable consistent greases.

Chlorofluorocarbons, which are significantly cheaper products
than fluorocarbons, have found a use along with the fluorocarbons as
lubricating oils. Chlorofluorocarbons are obtained by replacing all
atoms of hydrogen in hydrocarbons partially by chlorine, and partially
by fluorine. Chlorofluorocarbons according to their external form
are similar to fluorocarbons - colorless or yellowish liquids without

a smell. The introduction of chlorine into a fluorocarbon molecule increases its boiling point, improves the viscosity-temperature characteristic, but simultaneously somewhat lowers the thermo-oxidation stability.

The density of chlorofluorocarbons is somewhat lower than that of fluorocarbons. The antiwear properties of chlorofluorocarbons are better than those of fluorocarbons.

Fluorocarbon and chlorofluorocarbon oils can be used as noncombustible liquids for the hydraulic systems of aircraft, in the production of atomic energy, in rocket technology, etc.

Oils, consistent greases, and liquids based on fluorocarbons and chlorofluorocarbons based on fluoroparaffin, fluorinated mineral oils and polychlorotrifluoroethylene has been developed.

Fluorocarbon and chlorofluorocarbon oils today still have a high cost and therefore they are used only when other oils are not suitable.

C H A P T E R   XI

THE ENGINEERING BASES OF USING AVIATION OILS

1. Viscous Properties and the Pumpability of Oils

The methods of determining the viscosity of liquids were
examined in Chapter II. The viscosity of oils depends both on the
chemical composition and structure of the hydrocarbons of which
consists of oil, and on external factors: pressure, temperature, and
radioactive irradiation.

Dependence of the viscosity on the pressure. With a change
in pressure the viscosity of oils changes, moreover this dependence
will be different at different temperatures. At low pressures (up
to 50 kgf/cm^2) the viscosity of oil practically does not change. At
pressures up to 300-400 kgf/cm^2 this dependence has a practically
linear character (Fig. 81). At the pressures greater than 400 kgf/cm^2
this linearity is broken. Different oils change their viscosity under
pressure differently moreover the higher the temperature of the oil,
the less its viscosity changes from the pressure (Table 35).
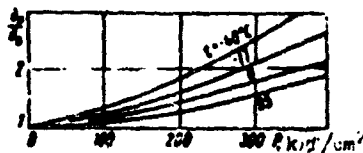
Fig. 81. Dependence of the
viscosity of mineral oil on the
pressure.

Oil	Multiplicity of growth of the viscosity			
	1000 kgf/cm^2		1500 kgf/cm^2	
	54°C	100°C	54°C	100°C
Mineral paraffin base	7	3	25	13
Mineral asphalt base	17	6	100	29
Castor	—	2	—	5

At pressures of the order of 15,000–20,000 kgf/cm^2 oils harden.
Approximately the change in kinematic viscosity depending on the
pressure can be determined approximately according to the equation
of of L. G. Gurnich

$$v_p = v(1 + kp)$$

where v_p — the kinematic viscosity at pressure p, cSt; v — the
kinematic viscosity at atmospheric pressure, cSt; k – the coefficient,
depending on the brand of oil (for light oils $k = 0.002$, for heavy –
0.003); p – the oil pressure, kgf/cm^2.

The dependence of viscosity on pressure can be calculated more
accurately according to the formula of M. P. Volarovich

$$v_p = va^p$$

where v_p — the kinematic viscosity of oil at pressure p, cSt; v —
the kinematic viscosity of oil at atmospheric pressure, cSt; a –
a constant quantity, equal for mineral oils to 1.002–1.004.

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The change in viscosity with a change in pressure should be considered during the calculation of engine bearings because in the bearings of modern aircraft engines the pressures can reach 900-1000 kgf/cm^2 and more.

Dependence of the viscosity on the temperature. The viscosity of oils changes considerably with a change in the temperature, moreover this dependence is different for different composition oils (Fig. 82). Inasmuch as the viscosity is one of the basic operating qualities of oils, research on the regularities of the change in viscosity due to the temperature is very important. The less an oil changes its viscosity with a change in the temperature, or, in other words, the more sloping the viscosity-temperature curve, the higher the quality of the oil. This is explained by the fact that oil with a gently sloping curve of the viscosity at high temperatures retains sufficient viscosity for the reliably lubricating engine parts, but at low temperatures the viscosity of such an oil is not so great, that starting the engine and the circulation of oil in the manifolds is hampered. A specification for oils gives the minimum viscosities at two temperatures and data about the slope of the viscosity-temperature curve either in the form of the size of the ratio of kinematic viscosity at a low temperature (50°C) to the viscosity of oil at a high temperature (100°C), or in the form of an index of viscosity.
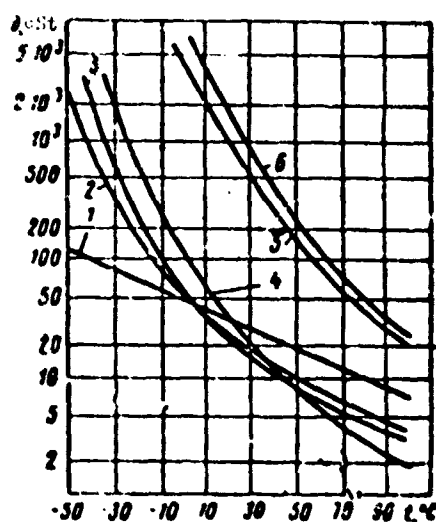
Fig. 82. Viscosity-temperature characteristics cf oils: 1 - dimethyl silicone; 2 - diester; 3 - polyglycol; 4 - MK-8 oil; 5 - MS-20 oil; 6 - MK-22 oil.

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The index of viscosity is a relative value showing the degree of the change in the viscosity of oil depending on the temperature, i.e., it characterizes the slope of the temperature curve of the viscosity of oil. It is determined with the help of two series of standard oils. Standard oils of the first series have a very gently sloping temperature curve of viscosity, and their index of viscosity is conditionally accepted as 100 units. Standard oils of the second series have a very steep temperature curve of viscosity, and their index of viscosity is accepted as zero. Oils of one and the same series differ from one another only in the amount of viscosity. Determining the index of viscosity is based on comparing the tested oil with two standard oils of the two series, which have at $98.8^{\circ}C$ a viscosity, equal to the viscosity of the tested oil. The index of viscosity of the tested oil is found with the aid of nomograms (Fig. 83), for which it is necessary to know the viscosity of oil at 50 and $100^{\circ}C$.
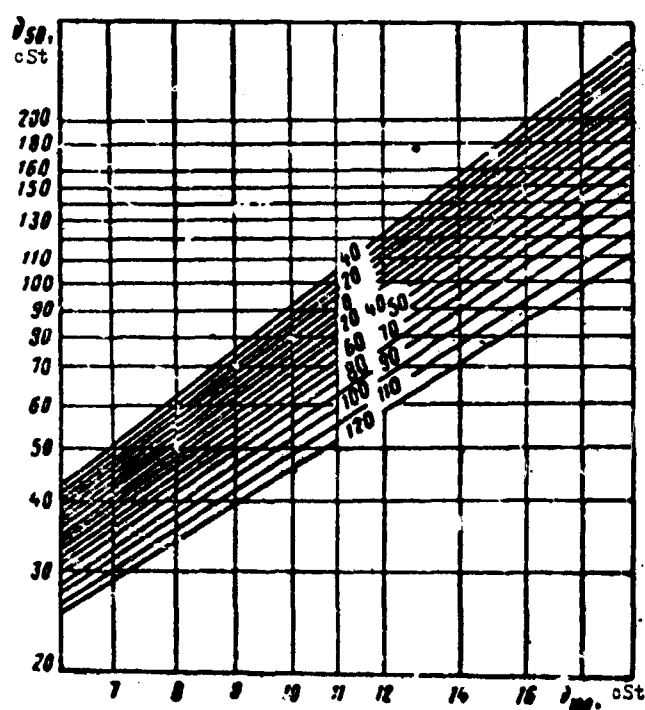
Fig. 83. Nomogram for calculating the index of viscosity.

Oils possessing a higher index of viscosity, i.e., a more gently sloping temperature curve of viscosity, are more preferable, than oil with a steep curve of viscosity, i.e., with a low index of viscosity. The degree of change in the viscosity of oils in a determined interval of temperatures can be evaluated by the temperature coefficient of viscosity (KB):

$$KB = \frac{\nu_{min} - \nu_{max}}{\nu_{cp}}.$$

For aviation oils most frequently coefficient of viscosity is in the interval 0-100°:

$$KB = \frac{\nu_0 - \nu_{100}}{\nu_{50}}.$$

Apparently, the lower in the given interval of temperatures the coefficient of viscosity, the less the dependence of the viscosity on the temperature.

With a decrease in the temperature of oil its viscosity increases (see Fig. 82). Because of this when starting cold engines cranking of the engine shaft, the circulation of oil through the lubrication system, spraying it, etc., is hampered. Oils whose viscosity rises sharply with a decrease in the temperature, i.e., oils with a steep viscosity-temperature characteristic possess poor starting properties. The higher the viscosity of petroleum oil, the sharper it increases with a decrease in the temperature. The viscosity-temperature characteristic of oil can be considerably improved by using special viscous additives.

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Of the substances possessing properties of viscous additives
various polymers have found a practical application: polyisobutylenes,
polymethacrylates, vinipols, and voltols. They represent the product
of the catalytic polymerization of isobutylene. Molecules of
polyisobutylenes are similar to long filaments or fibers and have the
following structure:

$$-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_2-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_2-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_2-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_3$$
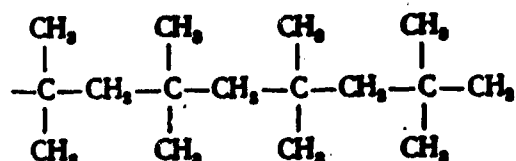
The higher the molecular weight of polyisobutylenes, the longer
the molecules. Presently polyisobutylenes have been obtained with
a molecular weight of more than 20,000. Polyisobutylene is a
slightly fluid sticky mass with a density of 20°C of about 0.880.
In mineral oils polyisobutylenes dissolve at 60-80°C in any ratios.
When the same quantity of polyisobutylenes of a different molecular
weight is added to oil the viscosity of the oil increases more
strongly, the higher the molecular weight of the polyisobutylenes.
Using viscous additives it is possible to increase the viscosity of
low viscosity oil at the basic operating temperature to the required
value preserving the slope of the viscosity-temperature characteristic,
peculiar to low viscosity oil (Fig. 84). The large low-mobility
molecules of the polymer decrease the transverse cross section of
space, about which the low viscosity component of the oil flows, and
they brake its current. Outwardly this is manifested as an increase
in the internal friction between the layers of oil, i.e., as an
increase in the viscosity. The basic deficiency of thickened oils
is the gradual failure ("fracture") of the molecules of the thickner
under the effect of external forces (for example, during the operation
of the oil in reduction gears and hydraulic systems).
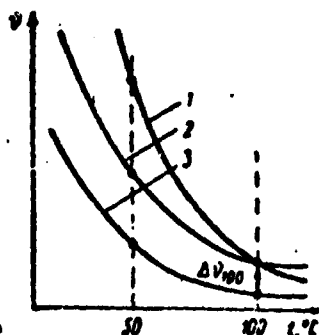
Fig. 84. Influence of an additive on the viscosity-temperature characteristic of oil: 1 - natural petroleum oil; 2 - thickened oil on a low viscosity base (the point of intersection of curves 1 and 2 - required viscosity at 100°C); 3 - low viscosity base.

Oils do not have a determined clearly expressed temperature of transition from the liquid to the solid state. The boundary of the transition is conditionally considered the temperature of the loss of mobility of the oil after cooling it under standard conditions. This temperature is called the thickening temperature.

The thickening of oil can be associated with two different processes: a gradual increase in the viscosity up to transformation of the oil into an amorphous glassy mass or the formation of a crystallic frame of high-melting paraffin hydrocarbons. During the production of oils to provide for a low thickening temperature an attempt was made to remove the high-melting paraffin from them. Furthermore, it is possible to decrease the thickening temperature with special additives - depressors. The effect of depressors is explained by their capacity to weaken the forces of molecular interaction between the paraffin crystals, in consequence of which the capability for forming a three-dimensional crystal lattice decreases.

2. The Lubricating Capacity of Oils

In cases when it is not possible to provide a liquid lubricant between friction parts, the wear of these parts and the size of the

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friction force depend on the properties of the oil, which can conditionally be called the lubricating properties. The better the lubricating properties of the oil, the less wear and loss to friction and the more reliable the protection of the friction surfaces from the gripping and jamming of metals.

The lubricating capacity of oils depends upon a number of factors, but the basic effect is shown by the physicochemical properties of the hydrocarbons and additives in the composition of the oil.

The lubricating capacity of the oils should be manifested in two positive qualities of oil: in the first place, in the capacity to avert wear of the friction surfaces under conditions of a stable boundary film of oil in the area of oxidizing (according to the classification of B. I. Kostetskiy) wear, i.e., the oil should possess antiwear properties; in the second place, in the capacity to move away to the side of large loads, large rates of a slip, and higher temperatures at the moment of rupture of the boundary film of oil and the onset of gripping of the metals, i.e., the oils must possess antiseizing properties.

In a number of cases oils possessing good antiseizing properties do not have good antiwear properties and vice versa.

This is explained by the fact that the antiseizing properties are caused by the chemically active substances present in the oils (in particular, substances containing S, Cl, P, O).

Under heavy friction conditions when high temperature develops on the surfaces of metals, the chemically active elements, connecting the friction surfaces with the metal form films, which present the contact of the bare metals and gripping of them. The more chemically active a lubricant the better its antiseizing properties. Under conditions of light boundary friction, when

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gripping of the metals is not observed, wear of the surfaces occurs
as a result of the formation and subsequent destruction and removal
from the surfaces of very thin films - the products of the interaction
of the chemically active elements of oil with the material of the
friction surfaces.

In this case the increased chemical activity of the oils leads
to an increase in the rate of wear.

It is understandable, that the antiseizing and antiwear char-
acteristics of the oils will change with a change in the properties
of the materials of the friction surfaces and the properties of the
the medium because the speed of the chemical processes, the amount
and properties of the surface films being formed depend on the
chemical properties of the material of the friction surfaces and the
properties of the gas medium.

Capital studies of the boundary friction of the antiwear and
antiseizing properties of oils have been conducted by the native
scientists B. V. Akhmatov, P. A. Rebinder, G. V. Vinogradov, and
others, and also by the foreign scientists Bowden, Taybor, Trell, and
others.

The most widespread method of evaluating the lubricating
capacity of oils are mechanized tests on instruments and friction
machines. Unfortunately, despite the large variety of machines and
friction instruments, thus far not one of them has received general
acknowledgement as a standard instrument for evaluating the
lubricating capacity of oils. In existing friction instruments and
machines the lubricating capacity of oils is evaluated according
to various indicators: by the size of the coefficient of friction,
the maximum load, which causes jamming of the friction parts, and
others. The most widely used machine for determining the lubricating
properties of oils under conditions of large contact loads during
the friction of solid steel surfaces is the four-ball machine.

To increase the lubricating properties of oils additives are
used.

3. The Stability of Oils

During the operation of an engine, the oil, undergoing the influence of high temperatures and the oxygen of the air, suffers chemical changes and partially vaporizes. On the parts adjoining the oil, various carbonaceous substances are deposited, and the properties of the oil itself change.

The stability of an oil is called its capacity to retain its composition and properties while working in an engine. The more stable the oil, the less it forms contaminants (deposits, varnish films, carbon deposits). The change in the quality of oil in an operating engine and the formation of carbonaceous deposits is primarily associated with the oxidation of oil. The oxygen in the air, entering into a reaction with molecules of oil, forms as a final result resins, asphaltenes, carbenes, etc.

The products of oxidation accumulating in the oil lead to a change in its physicochemical properties and the external form (viscosity increases, acidity increases, the oil grows dark, etc.).

The oxidizability of oils depends on many factors, the most important of which are the following:

chemical composition of the oil;

temperature conditions;

duration of oxidation;

catalytic effect of metals and the products of oxidation;

presence of water,

With an increase in temperature the rate of oxidation increases.

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At low temperatures (18-20°C) lubricating oils practically do not oxidize. A most thorough analysis does not reveal any substantial changes in the properties of oils, which were stored for five years under these conditions.

With an increase in the temperature to 200-300°C very considerable changes in the properties and composition of the oils are observed already in the first several minutes.

Influence of the temperature on the rate of oxidation of an oil

Temperature of heating of the oil, °C	Time of absorption of 5 mg oxygen in 1 g of oil
110	800 hrs
150	3 hrs
250	23 min
300	0.7 min

The oxidation of oils is considerably accelerated in the presence of metals or other substances which react catalytically to oxidation. Some metals (copper, iron, lead) accelerate oxidation: others (aluminum, tin) either do not have any effect, or even slow down the oxidation.

In the engine operating process the oil undergoes oxidizing processes in various temperature zones.

In the high-temperature zone of the engine (the combustion chamber of a piston engine) the oil is heated to temperatures of 350-400°C. In this case part of the oil loses volatile substances, is charred, and forms carbon deposits.

A study of the processes of carbon formation conducted by K. K. Papok, showed that the quality and expenditure of oil during the prolonged operation of an engine practically do not influence carbon formation.

In steady process along with carbon formation gradual burnout of the carbon deposit takes place. The rate of burnout depends on the engine operating temperature condition. The higher the temperature condition, the thinner the layer of carbon deposit.

In the medium temperature zone of an engine (the disc and bearings of the gas turbine of a turboprop engine, the side and interior walls of the piston in a piston engine, etc.) the oil is heated to a temperature of 200-300°C and is found in the form of a thin film on the surface of parts. Here part of oil vaporizes, part is oxidized and decomposes, forming a solid sediment - varnish. The process of varnish formation goes on continuously, its intensity increases with an increase in temperature. A film of varnish being a poor conductor of heat, leads to considerable overheating of the parts of an engine and as a consequence of this to their warping, jamming, and other dangerous consequences. In order to protect an engine from intensive varnish formation, oil is purified of a considerable part of resinous and other varnish-forming substances.

At the present time Prof. K. K. Panok and his colleagues developed methods and instruments for evaluating the volatility and varnish-forming capacity of oil, which is found in a thin layer on a metal surface. The thermal properties of oils are evaluated according to the following three standard methods:

thermal oxidation stability (method of K. K. Papok);

engine volatility, working fraction and tendencies the formation of varnish;

washing properties.

For a more complete evaluation of the possible behavior of oil in the process of varnish formation in an engine, it is necessary to consider the indicators obtained from all three methods.

The thermal oxidizing stability characterizes the rate at which oil at given temperature turns into a varnish film of a fully determined strength or determined composition, and is expressed by the time in minutes, during which it is formed. The more time necessary for the formation of such a film, the higher the thermal-oxidizing stability of the oil. Determination was accomplished according to GOST 4953-49 or GOST 9352-60 in a special varnish-former, the diagram of which is given in Fig. 85.
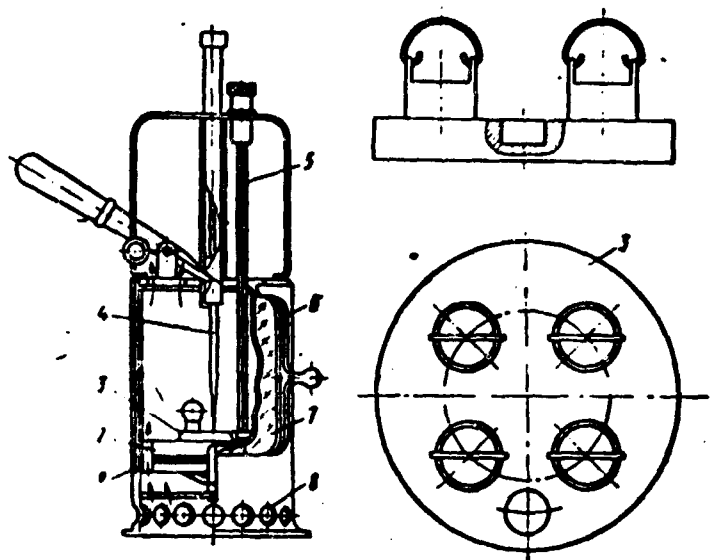
Fig. 85. Diagram of a varnish-forming device for determining the thermal oxidizing stability of oils: 1 - electric heater; 2 - metal plate; 3 - disc with evaporators; 4 - rod; 5 - thermometer; 6 - housing; 7 - glass door; 8 - opening for the admission of air.

When conducting the experiment disc 3 together with metal rings and handles are installed in the varnish-forming device on a heating plate and preheating is accomplished. After the assigned temperature is established, 0.05 g of the tested oil is introduced into each ring with the aid of a special pipette. Having maintained the

instrument at the assigned temperature until the oil in the rings is
transformed into a dark varnish film and having fixed this time, a
disc with the rings is removed and cooled at room temperature for
an hour. After cooling every ring is torn off from the disc with the
aid of a lever dynamometer, noting the required stress, calculated as
an average arithmetical for all four rings. Since the stress required
to detach the rings, within the limits 0.5-3.0 kgf, depends linearly
upon the duration of the experiment, then, having repeated the
experiment 2-3 times and having built a graph (Fig. 86), the time,
corresponding to the formation of a varnish film with a strength of
1 kgf is found.
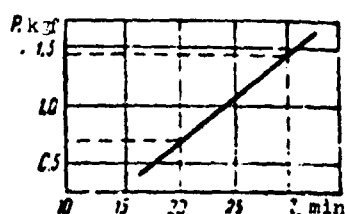
Fig. 86. Graph of the results
of the experiment for determining
the thermal stability (GOST
9352-60).

According to GOST 9352-60 the thermal oxidizing stability is
determined in a varnish-forming device by heating 0.035-0.040 g of oil
in a special evaporator, which is a steel flange 22 mm in diameter
with the height of the collar of 1 mm. Four such evaporators are
used in one experiment. After the oil is oxidized, one evaporator is
removed from the disc and the time taken to remove it is noted.
Subsequently after each 5-10 min the evaporators are removed one by
one. The evaporators are weighed and the quantity of the working
fraction remaining and quantity of varnish formed on the evaporators
is determined. On the basis of the data obtained a graph of the
dependence of the working fraction [WF] (PФ) and tendency towards th
formation of varnish Л on the time (Fig. 87) is constructed. Using
the graph the time if found (in minutes), during which the tested oil
at the assigned temperature turns into a varnish residue consisting
of 50% of the working fraction and 50% varnish. This time will also
determine the thermal oxidizing stability of the oils.
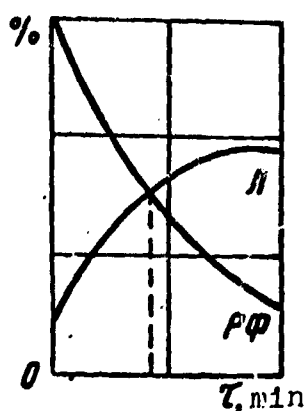
Fig. 87. Determination of the
thermal oxidizing stability from
the intersection of the curves
(GOST 9352-60).

The engine volatility together with the working fraction and
the tendency of oil towards the formation of varnish characterize the
thermal stability of an oil. The determination is accomplished in
the following manner: a metal disc from four metal flanges or evapor-
ators is placed in a varnish-forming device (see Fig. 85) and is
heated to a given temperature. Then 0.05 g of the oil being tested
are poured into each evaporator. Having kept the evaporators with the
oil in the varnish forming device for the given time, they are taken
out, allowed to cool, and are weighed. The weight loss caused by the
vaporization of the light fractions of the oil, expressed in
percentages, is the index of the engine volatility of the oil. From
the residue the liquid part is extracted which taken as the working
fraction, and the solid carbonaceous substances remaining in the
evaporator in the form of a thin black coating is taken as the varnish.

The engine volatility, working fraction, and varnish are
expressed in weight percentages from the oil sample. The sum of the
digital indexes of engine volatility, working fraction, and varnish
equals 100.

Table 36 gives the indicator of a number of oils according to
their thermal stability.

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Table 36. Indicators of oils at 250°C after 30 min of heating.

Indicators, %	Machine	Avtol 10 (a lubricating oil)	MK	Synthetic	Castor
Engine volatility	84	80	53	67	34
Working fraction	16	17	34	9	1
Varnish	0	3	13	24	65

The indicators of the **engine volatility, working fraction,** and varnish change depending on the temperature and the length of time the oil is held in a thin layer on the metal surface (**Fig.** 88 and 89).
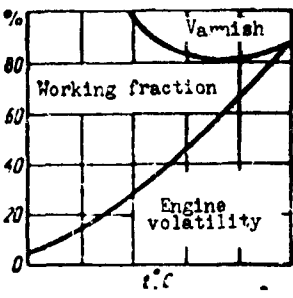
Fig. 88.
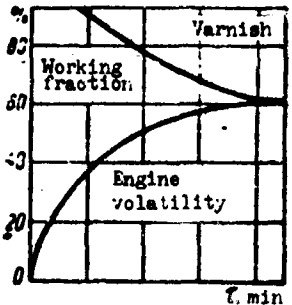
Fig. 89.

Fig. 88. Change in the engine volatility, working fraction, and varnish depending on the test temperature.

Fig. 89. Change in the engine volatility, working fraction, and varnish depending on the time the oil is held at a high temperature.

Washing properties - this is the capacity of the oil to retain resinous products in itself, preventing them from being deposited on the engine parts. The washing properties of oils are determined when they are tested on the (Papok, Farubin, and Vipper) [PZV] (ПЗВ) device according to GOST 5726-53. A diagram of the device is shown in Fig. 90. Having created the required temperature conditions using electrical heating equipment 250 ml of oil are tested for 2 hours on this device. After termination of the test the device is dismantled the cylinder and a piston conclusion is made about the washing properties of the tested oil. The evaluation is given in balls on an arbitrary scale, where a completely clean piston surface (without varnish) is taken as 0 and a surface coated with varnish of a black color is taken as 6 balls (maximum varnish formation).
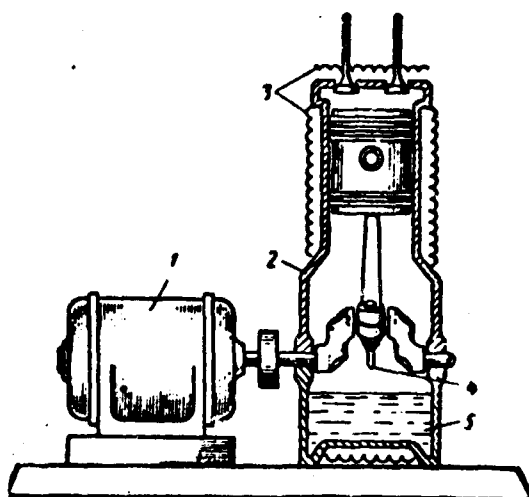
Fig. 90. Diagram of a device for determining the washing properties of oils: 1 - electric motor; 2 - engine; 3 - electrical heating elements; 4 - scoop; 5 - oil.

In the low-temperature zone of an engine (the gear box of the units of a turbojet engine, the crankcase of a piston engine) the temperature of oil is found within the limits 50-120°C. Here oil has a large area of contact with catalytically active nonferrous

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metals (including suspended particles from their wear). In connection with spraying and foaming, the oil has a large area of contact with the air. These conditions facilitate the oxidation of oil and the formation of a sticky greasy dark colored mass - sludge, noticeable in piston engines in the crankcase, on oil filters, and in other zones of relatively low temperature.

Analyses show, that a sludge consists of the products of the oxidizing polymerization of hydrocarbons - hydroxy acids, resinous-asphalt and carbonaceous substances (carbenes and carboids), and also water and oil.

In view of the extremely negative effect of carbon deposits, varnish, and sludge on the reliability and longevity of engines and aggregates the use of various antioxidant and washing additives to the oils was suggested as one of the measures to decrease the formation of deposits.

Substances which break down the oxidizing chains and which do not allow the development of an antioxidizing process are used as antioxidant additives. Furthermore, an antioxidant effect is also observed in the case where an additive passivates the positive catalysts of oxidation - metals. In this case the additive along with the antioxidant function also possesses an anticorrosion function because the films it forms on metal shield the metal from corrosion. As antioxidant additives a number of chemical compounds of an amino, phenol character, and compounds, containing sulfur, phosphorus, and others have been proposed. Washing additives also find practical application. But these additives do not remove the already formed deposits, but only prevent their formation. It is proposed, that washing additives either brake the oxidizing processes and decrease the amount of hydroxy acids and asphaltenes, or they deepen oxidation with the translation of hydroxy acid and asphaltenes into products of a deeper polymerization. Furthermore, washing additives prevent the adhesion of oxidation products to the surfaces of engine parts.

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In a number of cases the additives strengthen the capacity of oils to the formation of highly dispersed stable suspensions, of insoluble (or poorly soluble) in oil products of oxidation, protecting them from coagulation by means of the adsorption of the additive on the dispersed products in the oil.

Each of the enumerated properties can be inherent to different additives in a different degree, and respectively the effectiveness of their effect can be different.

Some of the additives put into the oil are multifunctional because they simultaneously possess a washing action which improves the lubricating capacity and show antitrust and antioxidant actions.

4. The Corrosion Properties of Oils

Aircraft lubricating oils should not have a corrosive effect on the materials of the engine parts. More than that, oils should themselves shield the engine parts and other aggregates from corrosion. To avoid corrosion by acting standards in oils a requirement is provided for the absence in oils of water-soluble acids and alkalis and the content of organic acids not soluble in water is strictly limited.

The lack of water-soluble acids and alkalis in oils is checked qualitatively by the same method that was shown for a corresponding check of fuels, but to facilitate the extraction of water the oil is preliminarily heated to 70-80°C (GOST 6307-52). The presence in water of insoluble organic acids is determined quantitatively by their extraction from the oil by boiling ethanol and by subsequent titration with an alcohol solution of KOH in the presence of an indicator (for example, a phenolphtnalein). The presence of organic acids in oils is expressed by an acid number, i.e., by a number of mg KOH, necessary to neutralize 1 g of oil (GOST 5985-51).

The corrosion of metals under the action of organic acids found

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in the oils depends on the quantity and the properties of these acids, and also on external conditions. Thus, for instance, the corrosion activity of organic acids very strongly increases in the presence of even a small quantity of moisture in the oils. The organic acids found in lubricating oils act on some nonferrous metals (and their alloys) considerably more intensively, than on ferrous metals.

The corrosion properties of oils are evaluated according to GOST 5162-49 (H. A. Pinkevich method). The instrument for determining the corrosion properties of oils (Fig. 91) consists of an oil bath 6, glass test tubes 5, into each of which 80 ml of the oil to be tested is poured, and mechanism 2, which provides for the alternately sinking standard size lead plates 4 into the test tubes with the oil, heated to 140°C, and their extraction from them. The plate is immersed 15 times per minute, the duration of the test is 50 hours. The degree of corrosion is determined according to the loss in weight of the plate in grams per square meter.
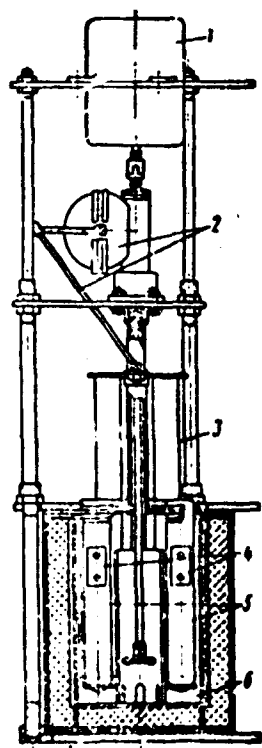
Fig. 91. Diagram of an instrument for determining the corrosion properties of oils: 1 - electric motor; 2 - mechanism for moving the plates; 3 - suspension; 4 - lead plate; 5 - test tubes with the oil being tested; 6 - oil bath.

To increase anticorrosion properties of oils special additives are added to them, the effect of which is explained by the passivation of the metal (alloy) surface and by the formation of a thin protective film on its surface, which prevents the further action of corrosion agents.

5. Radiation Resistance of Lubricating Oils

Under determined conditions lubricating oils can undergo the influence of nuclear radiation. In this case a number of properties of the oils changes considerably.

In the first place the viscosity of the oil changes, moreover this change can be very considerable. Fig. 92 gives the curve which characterizes the change in the kinematic viscosity (at 38°C) of mineral oil under the effect of radiation by neutrons (in a nuclear reactor) and a graph is given of the dependence of the change in the viscosity of turbine oils of various initial viscosities at 38°C under the effect of different doses of radiation. Under the effect of radiation other characteristics of oil also change. Thus, with an increase in the dose of radiation from 0 to $2.9 \cdot 10^8$ Rd the flash temperature decreases by 2 times, the volatility increases by 10 times and the acid number by 2.5 times.

Absorbed dose of radiation 10^8 Rd
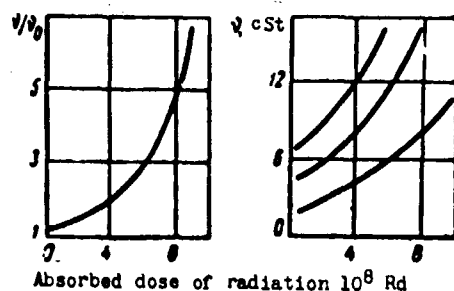
Fig. 92. The characteristic of the radiation resistance of oils.

In connection with this the additional requirements of radiation resistance should be set forth for oils which may undergo radioactive radiation in the process of work.

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6. Control Indicators of the Quality of Oils

The density of oils is determined in the same manner as is the density of fuels. To determine the density with an areometer the oil is diluted with an equal volume of a kerosene or gasoline of a known density, the density of the obtained mixture is determined and then according to a formula the density of oil is found

$$d = 2d_1 - d_2.$$

where d – the density of oil; d_1 – the density of the mixture; d_2 – the density of the solvent.

Flash ignition temperatures. Oil vaporizes upon heating. The vapors mixing with air, form a flammable mixture.

The lowest temperature, up to which it is necessary to heat the oil in order that its vapors would form a mixture with air that would ignite when a flame was introduced to it is called the flash temperature of the oil.

The temperature of heating of the oil, at which not only will the oil vapors ignite upon presentation of a flame to them, but the oil itself will burn is called the ignition temperature of the oil.

In determining the flash temperature according to GOST 4333-48 and GOST 6356-52 the oils are heated at a determined rate of increase in the temperature up to the moment until a flash is noted upon the presentation of a flame to the surface of the oil. The ignition temperature is determined in the same manner.

In an open type instrument (Fig. 93) the flash temperature of pure mineral oils is found as 20-30° higher than in a closed type instrument (see Fig. 18), as a result of the dispersion of part of the oil vapors.
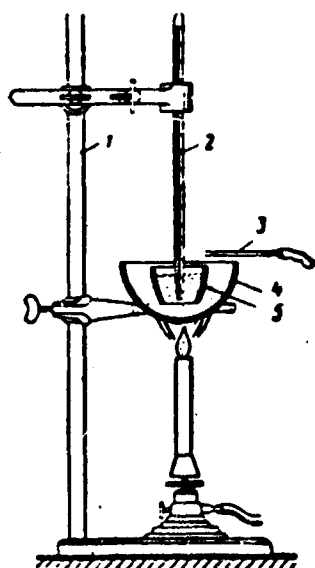
Fig. 93. Diagram of an open
type instrument for determining
the flash temperature of oils:
1 - support; 2 - thermometer;
3 - burner; 4 - external cru-
cible; 5 - internal crucible.

The flash temperature in an open instrument is distinguished from
the ignition temperature by approximately the same value. Very low
flash and ignition temperatures characterize the flammability of oil
and indicate the presence of random impurities, for the most part
fuel, in it.

Ash content. The residue obtained from the evaporation and
heat treatment in a porcelain crucible of a determined sample of oil
and expressed in percentages to the weight of the oil is called the
ash content.

The ash content in pure petroleum oil should be minimum. The
presence of considerable quantities of ashes indicates poor cleaning
of the oil, the presence of various salts and mineral mechanical
impurities, the presence of additives in the oil.

The method of determining the ash content according to GOST
1461-52 is reduced to the slow evaporation of a sample of oil and
then to the heat treatment of the carbonaceous residue formed after

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evaporation at dark red incandescence to complete ashing.

The coking capacity of oil. The essence of determining the
coking capacity according to GOST 5987-51 consists of the following:
the oil, heated to a high temperature without the access of air,
evaporating and decomposing, forms a coke-like residue. The coke
obtained is expressed in weight percentages with respect to the oil
taken. In the beginning it was proposed that there exists a direct
connection between the coking capacity of oil and the carbon formation
in an engine. For the last decades many varying studies were
conducted for the purpose of finding this dependence. It was
established, that the coking capacity of oil depends on the chemical
composition of the oil, the degree of cleaning of the oil; that with
an increase in the viscosity of oils, equal to origin and cleaning,
the coking capacity increases, but the connection between the coking
capacity of oil and the amount of carbon deposited in the combustion
chamber of an engine could not be established.

Today the coking capacity as an indicator of the quality of
oil although it continues to remain under the technical conditions of
almost all aviation oils, but does not have an independent value,
only together with other indicators is it useful in determining
origin of the oil for workers and users as a control indicators.

Mechanical impurities and water. All foreign bodies found
in oil in a suspended state or in a deposit (dust, sand, products
of wear, etc.) refer to mechanical impurities.

In fresh oils mechanical impurities and water should be absent.
Determining the mechanical impurities according to GOST 6370-52
consists of the following: a determined sample of oil is diluted with
gasoline and filtered through a dried and suspended paper filter.
After this the filter is dried and weighed, the amount of mechanical
impurities obtained is expressed in weight percentages to the oil.

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The water content in oil is determined for fresh oils of a qualitative breakdown (by the cracking or frothing method), and for waste oils by the quantitative method according to GOST 2477-44: 100 ml of oil is mixed with 100 ml of ligroin. The mixture is heated in a metal flask. The evaporating particles of water are condensed in a refrigerator and are gathered in a glass receiver.

C H A P T E R   XII

OILS FOR AIRCRAFT JET ENGINES

1. Operating Conditions of
Oil in a Turbojet Engine

The principal peculiarity of the lubrication system of gas-turbine
engines is the fact that the oil is not in contact with the
burning zone of the combustible mixture. In connection with this
the expenditure of oil in gas-turbine engines is considerably less
than in piston engines, and is caused only by the losses of oil
through the blower system.

In the basic friction nodes of a turbojet engine the antifraction
bearings are ball bearings or roller bearings. Thus, the basic
type of friction in a turbojet engine is rolling friction. The
coefficient of the friction of a rolling bearings comprises on
the average 0.002-0.004 while in slip bearings the coefficient of
friction can reach a value of 0.01. Therefore, the investments of
power to overcome the forces of friction in turbojet engines are
comparatively small. The insignificant starting twisting moment of
the rolling bearings considerably facilitates the starting of an
engine at low temperatures. Rolling bearings require small quantities
of lubricant and can operate reliably on low viscosity lubricating
oils. The bearings of a compressor when operating are heated to
approximately 100-150°C, the bearings of a turbine to 150-200°C,
and after the engine stops because the circulation of oils stops
and because of external blowoff the temperature of a bearing can
grow to 250°C. This facilitates the vaporization of oil, and in

the case of the presence in it of unstable component parts, creates conditions for varnish formation.

Besides lubricating the main bearings, the oil provides for lubrication of the gear and pinion of the unit drives, where the operating conditions of the oil is relatively light due to small specific loads and rates of slip.

Oil, when operating in a turbojet engine, can undergo the influence of temperatures from -50-60 to 200-270°C. The oil comes in contact with the various metals and alloys from which the parts of the oil system and engine have been made.

At high temperatures the low-boiling low-viscosity components of oil vaporize which causes an increase in the expenditure of oil and an increase in the viscosity of the oil remaining in the system. At a working temperature of 120°C the volatility of low viscosity mineral oil is 8-35 times greater than that of highly viscous mineral oils. With an increase in the flight speeds and in the power of engines and temperature in the friction nodes, will grow, therefore, the requirement for the thermal stability and volatility of oils should rise. At operating temperatures in the friction nodes above 300-350°C petroleum lubricating oils are not suitable for use.

An important operational property of oils for turbojet engines is the ignition temperature. Falling into a turbine bearing, which is located near the hot nodes of the engine, the oil undergoes the influence of high temperatures which can cause i ignition.

In some gas-turbine engine designs there is a front bearing located in the inlet channel of the diffuser. In this case its temperature reaches -50-60°C. This circumstance forces one to consider its low-temperature properties (viscosity, pumpability, thickening temperature) when selecting an oil for the gas-turbine engine.

Bench tests conducted at a temperature of -54°C showed that
during the operation on commercial mineral oil the pressure in the
oil system rapidly decreases. After ten minutes of engine operation,
the pressure on output from the oil filter was equal to zero. This
is explained by the fact that at a temperature lower than zero an
increase in the viscosity of the oil causes a sharp decrease in the
capacity of the oil pump (Fig. 94). The critical temperature, below
which the standard pumpability of oil in the system is broken depends
on the viscosity of the oil at low temperatures. The level of
viscosity, at which the standard pumpability begins to be broken,
constitutes about 5000 cSt according to experimental data. At
viscosity of about 20,000 cSt the supply of oil into the friction
nodes of an engine completely ceases. Commerical low viscosity oils
(with a viscosity at 50°C of 7-8 cSt) achieve a viscosity of 5000 cSt
at temperatures of -35-40°C. For special oils this level of viscosity
can be reached at -50-55°C.
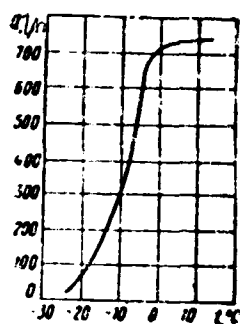
Fig. 94. Dependence of the capacity of
an oil pump on the temperature and,
therefore, on the viscosity of the oil
being pumped (viscosity at 50°C equals
60 cSt).

The pumpability of oils f   jet engines can be characterized
both as the critical temperature at which the supply of oil to the
friction nodes begins to be broken, and as the temperature at which
the supply of oil ceases completely. These temperatures are given
in Table 37.

Table 37. Temperature limits of the pumpability of oils for jet engines

Oil	Kinematic viscosity, cSt, at 50°C	Temperature, °C, at which the supply of oil	
		is disrupted	ceases
Mineral	7,0	—43	—51
"	150,0	— 1	—15
Synthetic........	7,0	—51	—59
"	7,6	—48	—56

If, from the point of view of pumpability, oils for jet engines must have the lowest necessity possible, especially at low temperatures, then it should always be remembered, that a decrease in the viscosity of oil decreases the work resource of the bearing. To provide the necessary work resource for heavily loaded bearings of gas-turbine engines, it is necessary that the viscosity of the oil in the operating conditions of an engine provide reliable lubrication. For the oils of gas-turbine engines the level of viscosity is controlled at 50°C.

Since in modern turbojet engines the expenditure of oil is insignificant, a relatively small quantity of oil (5-13 *l*) is poured into the lubrication system. To provide for the elimination of heat from the friction nodes the oil circulates in the system and passes through the engine about 70-100 times an hour. In connection with the fact th. ̂ the oil in an engine is intensively mixed with air and foams, it is necessary to set forth raised requirements for its stability.

2. Brands of Oils for Turbojet Engines

The described operating conditions of oil in turbojet engines create great difficulties when selecting an oil.

Presently in the USSR the following low viscosity distilled oils are used for turbojet engines MK-8, MK-8P, MS-6, MK-6, transformer, and also the synthetic oil VNII-NP-50-1-4F. The technical requirements for these oils are given in Table 38.

Table 38. Technical requirements for oils for turbojet engines

Indicators	MS-6 (GOST 11552-65)	MK-6 (GOST 10328-63)	MK-8 (GOST 6467-66)	MK-8P (GOST 6467-66)	transformer (GOST 982-56)	VNII NP-50-1-4F (GOST 13076-67)
Viscosity kinematic, cSt:						
at 100°C, not less than....	—	—	—	—	—	3,2
" 50°C, " " "	6—6,3	6—6,3	8,3	8,3	9,6	—
" 20°C, not more than....	18	19	30	30	30	—
" -40°C, " " "	1 700	3 300	—	—	—	2 000
" -54°C, " " "	—	—	—	—	—	11 000
Stability of the viscosity at -54°C:						
change the viscosity after 3 h, % not more than	—	—	—	—	—	±6
viscosity after 3 h cSt, not more than................	—	—	—	—	—	11 700
Acid number, mg KOH per 1 g of oil, not more than....	0,04	0,04	0,04	0,04	0,05	0,22
Temperature of thickening, °C, not higher than..........	—55	—60	—55	—55	—45	—60
Flash temperature, °C:						
in a closed type instrument, not below.................	140	140	135	135	135	—
an open type instrument, not below.................	—	—	—	—	—	204
Stability:						
sediment oxidation, %, not more than	is absent	0,1	0,1	0,15	0,1	—
Acid number after oxidation, mg KOH per 1 g oil, not more than................	0,15	0,35	0,25 at 120°C	0,60 at 175°C за 10 h	0,35	2,0 at 175°C за 72 h
Ash content, %, not more than..	0,005	0,005	0,005	0,005	0,005	0,1
Sulfur content, not more than..	0,7	0,14	0,14	0,14	—	—
Content of water soluble acids and alkalis.............			Are Absent			
Content of mechanical impurities....................			Are Absent			
Water content.............			Are Absent			
Density at 20°C, g/cm³, not more than....................	0,860	0,900	0,885	0,885	—	0,926

The MK-8 and transformer oils according to their physicochemical properties do not provide for the reliable operation of an engine over a wide range of temperatures. The substantial deficiency of

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these oils is the inadequate stability of their fractional composition
which leads to a deterioration of the viscosity-temperature and
starting properties which impairs the starting of engines with the
temperature of the external air below -25°C, and also the inadequate
thermooxidizing stability at high temperatures. To increase
the stability an antioxidant additive has been added to the MK-8P
oil.

The oils MK-6 and MS-6 are of a narrow fractional composition.
The level of basic viscosity for them is somewhat lower, than
that of MK-8 (6 cSt instead of 8), but in greasing properties they
practically are not distinguished from MK-8 oil. Because of the
narrow fractional composition, MS-6 and MK-6 oils have a lower
thickening temperature (-60°C instead of -55°C for MK-8) and a lower
value of viscosity at -40°C (3000 cSt instead of 7000 cSt for MK-8).
The temperature limits of boiling of the oils MS-6 and MK-6 are
290-360°C while for MK-8 oil -- 260-420°C.

When starting jet engines with the outside air temperature
below -25°C it is necessary to preliminarily heat the engine, if
its lubrication system is filled with MK-8 or transformer oil. When
operating an engine with MS-6 and MK-6 oils it can be reliably
started without preheating down to a temperature of -37°C.

3.   Peculiarities of Lubricants for Turboprop Engines

In a turboprop engine the power from the turbine shaft is
transmitted to the propeller by a step-down reducer. The gears of
the reducer operate under high loads because the transmitted power
in modern turboprop engines can reach several thousand horsepower.
Extremely high surface stresses appearing along the line of
engagement of the teeth of the revolving gears are characteristic
for the operation of oil in the reducers of turboprop engines.

Because of this increased wear of the gears of the reducer is
observed. Reducers of turboprop engines in principle require
completely different oils, than do the rolling bearings: viscous
oils with a high lubricating capacity are necessary for them. The
maximum load on the teeth of a gear at which jamming occurs, depends
on the viscosity of the oil and its lubricating capacity (Fig. 95).
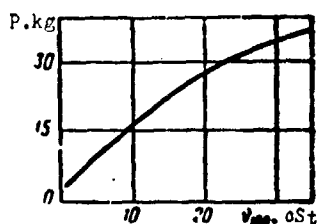
Fig. 95. Dependence of the maximum
load of jamming of the reducer gears of
a turboprop engine on the viscosity of
the oil.

In connection with the peculiarities of work of a turboprop
engine, to provide for its reliable operation mixtures of low
viscosity distilled oils MK-8 or transformer with the highly viscous
residual oils MS-20 or MK-22 which possess a good lubricating capacity
are presently being used as lubricants.

The synthetical VNII NP-7 has also been developed for lubricating
turboprop engines. The basic characteristics of oils for
lubricating turboprop engines are given in Table 39.

A mixture of oils with a large viscosity is used in high power
turboprop engines. Engines serviced with a mixture of MK-8 and
MS-20 or MK-22 oils are reserviced with a mixture of transformer oil
and MS-20 or MK-22. During preparation the mixtures of oil are
taken by volume.

Mixing is accomplished at a temperature of 15-20°C with thorough
mixing for 20-25 min. After the termination of the mixing the
correctness of preparation of the mixture is checked using the
viscosity at 100°C, which must be within the limits 4-6 cSt for a

low viscosity mixture and not less than 10 cSt for a high viscous mixture. If the viscosity of the mixture differs from the indicated amount, it is necessary to correct the mixture.

Table 39. Technical requirements for oils for turboprop engines

Indicators	Mixture of 75% MK-8 or transformer and 25% MS-20	Mixture of 25% MK-8 or transformer and 75% MS-20	VNII-NP-7
Density at 20°C gf/cm³.............	0,8—0,9	0,8—0,9	0,918—0,922
Viscosity kinematic cSt, at:			
100°C	4,0—6,0	10,0—13,0	7,5—8,0
50°C	15—20	55—71	—
-35°C not more...................	4500	—	7500
Flash temperature in an open crucible, °C, not below............	135	150	110
Thickening temperature, °C, not higher than....................	—40	—20	-60
Acidity, mg KOH per 1 g of oil not more than...................	0,005	0,10	0,6
Ash content. %. not more than.......	0,005	0,005	—
Coking capacity, %, not more than...	0,15	0,45	—
Water content........................		Is absent	
Content of water-soluble acids and alkalis........................		Are absent	
Content of mechanical impurities....		Are absent	

4. Change in the Physicochemical Properties of Oil During Operation in a Jet Engine

During the operation of jet engines the quality of the oil found in the lubrication system changes. These changes take place as a result of the oxidation of oil at high temperatures, vaporization of part of the oil, the accumulation of the products of wear in it, mechanical impurities, and water.

In the process of the operation of an engine an increase in the viscosity of oil occurs in connection with the fact that part of the light hydrocarbons from the oil vaporize. The character of the change in the viscosity of oils during the operation of an engine is shown in Fig. 96. The viscosity of oil increases most intensively in the first 5-10 h of operation of an engine, then the process is stabilized. The change in viscosity in the process of the operation of an engine should be considered during the operation

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of an aircraft under low temperature conditions. If one assumes
that an engine can be easily started with the viscosity of oil
not more than 4000 cSt, then with fresh MK-8 oil starting is possible
at temperatures no lower than -35°C (Fig. 97). Having operated
50 h the starting of an engine can be accomplished only at
temperatures no lower than -25°C. The sharper the changes in the
viscosity of oil in the process of the operation of an engine, the
faster its pumpability deteriorates at low temperatures.
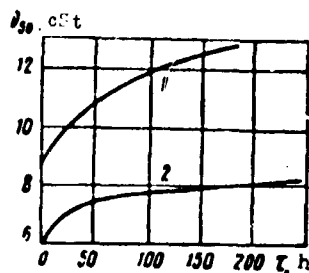
Fig. 96. Change in the viscosity of oil
in the process of its operation in an
engine: 1 — MK-8; 2 — MK-6.
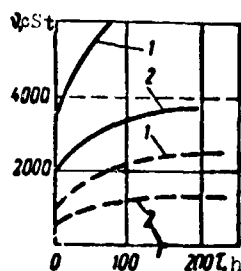
Fig. 97. Change in the viscosity of oil at
negative temperatures in the process of the
operation of an engine: 1 — MK-8; 2 — MK-6 ---
at t = 25°C; —— at t = -35°C.

In the process of the operation of an engine flash temperature
can increase (Fig. 98). This is also associated with the loss of
the light fractions of the oil in the first hours of the operation
of an engine.
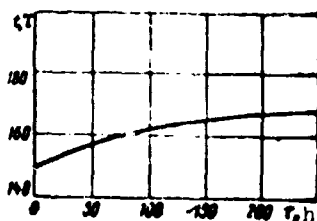
Fig. 98. Change in the flash tempera-
ture of oil in the process of the
operation of an engine.

The accumulation of mechanical impurities in oils during their operation in jet engines occurs basically in the first 50-100 h of operation, whereupon their content practically does not change (Fig. 99).
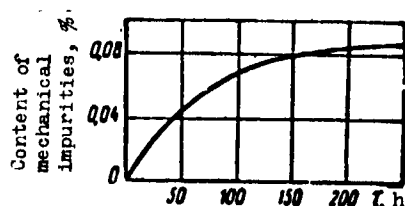
Fig. 99. Change in the mechanical impurities content in the process of the operation of an engine.

The acidity of the oil increases proportionally to the number of hours the engine has worked (Fig. 100), and only by adding fresh oil is the amount of acidity lowered to a level, close to the initial.
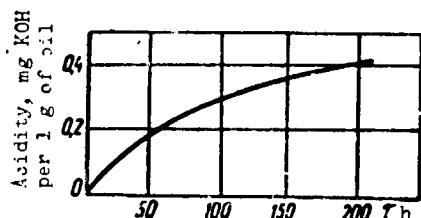
Fig. 100. Change in the acidity of oil in the process of the operation of an engine.

5. Peculiarities of Engine Lubricants for Supersonic Passenger Aircraft

The engines of supersonic passenger aircraft will be similar to modern gas turbines, but with higher load values on the bearings and the gears, with higher temperatures of the gas and air streams. The quantity of heat liberated as a result of friction will increase considerably. Oils in the engine will undergo the influence of higher temperatures and contact stresses.

At M = 2.5 the volumetric temperature of oil in a tank can rise to 200-220°C, the temperature of oil in the zone of a bearing — to 300-320°C.

At the same time the oil according to its operational properties should be such, that it can provide easy starting at low temperatures on earth.

The boiling temperatures of substances in the composition of the oil, should be such that the vaporization of a large quantity of oil during a prolonged flight at great altitude is avoided.

Thus, the temperature range, in which oil should retain satisfactory operational properties is from -60 to +350°C.

For such rigid conditions petroleum oils will hardly be suitable, even with modern methods of obtaining and cleaning.

Oils for the engines of supersonic passenger aircraft will be synthetic liquids with multifunctional and narrow-purpose additive which are stable at high temperatures.

Specifically, several complex esters which possess the following basic operational features will serve as the base for the oils:

thermooxidizing stability at temperatures up to 350°C;

good antiwear properties under high contact stresses;

low viscosity at low temperatures (less than 12,000 cSt at -50°C);

good heat-physical characteristics over a wide range of temperatures (from -60 to 350°C);

good anticorrosion properties.

Along with the selection of the oil base, the selection of the optimum combination of additives, which effectively avert oxidation, corrosion, carbon formation, improve the antiwear properties, etc., has a very important value.

The basic indicators of an oil thermostable to 350°C for supersonic passenger aircraft should have approximately following values:

Viscosity, oSt:

at 250°C, not less than.....................	1,0—1,5
at 100°C, not less than.....................	6,5—7,0
at -50°C, not more than.....................	12 000
Flash temperature, °C, not lower than.............	300
The losses due to vaporization over 10 h, %, not more than...................................	10—15

C H A P T E R   XIII

OILS FOR AIRCRAFT PISTON ENGINES

1. Operating Conditions of Oil
in Piston Engines

The basic friction nodes of aircraft piston engines are the
most stressed of all types of internal combustion engines. Further-
more, in a piston engine the oil accomplishes the function of a
sealer between the combustion chamber and the crankcase, therefore,
it is next to the burning zone of the combustion mixture. This
makes the operating conditions of the oil in the engine very
difficult.

Lubrication of the friction nodes and the elimination of heat
from the parts of an engine is accomplished with oil by circulating
and bubbling it. The circulation of oil is accomplished under
pressure of 4-10 kg/cm^2. From 1100 to 3800 l/h of oil (depending
on the type of engine and its operating conditions) are pumped
through an aircraft engine. With the relatively small capacities
of the oil tanks after 1 h a particle of oil manages to go through
the engine tens of times.

In pistc . engines the basic type of bearings is the slip
bearing. The specific pressure in the slip bearings reaches
600-800 kg/cm^2. The temperature of the bearing depends mainly on

the work of friction, temperature; and the quantity of the oil which
flows through it. In modern engines the temperature of a bearing
fluctuates within the limits 60-140°C.

In an engine oil operates under various temperature conditions:
from 80 to 2500°C.

Temperature conditions of parts during the
operation of a piston engine, °C.

Combustion chamber	1500—2500
Exhaust valve disc	800—900
Intake valve disc	200—250
Cylinder head (at the rear spark plug)	250—280
Skirt	140—180
Piston (bottom)	220—270
Crankcase	90—100

Part of the oil circulating in an engine penetrates the
combustion chamber and burns together with the fuel. The expenditure
of oil connected with this depending on the type of engine and its
technical state can be from 5 to 25 g/hp-h.

A large rate of movement is characteristic for the friction
nodes of aircraft engines. Thus, for instance, the rate of slip
of the basic friction parts is found within the limits 6-15 m/sec.
The oil in an engine comes in contact with the most varied metals
and alloys: steels of various types and various treatment, aluminum
alloys, babbitts, plumbous bronze, cadmium-silver alloys, and others.

Cleaning of the oil during the operating is accomplished with
the aid of a plate filter, and also by means of centrifuging in
the hallows of the connecting-rod crankpins: the contaminants
contained in the oil are thrown out by centrifugal forces to the
periphery of the pin and they form a sediment.

In order to provide for liquid lubrication of the friction
nodes under conditions of a high specific pressure and high tempera-
ture, and also for good sealing of the gaps between the piston and

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the cylinder, the oil should be of high viscosity (on the order of 20-22 cSt) at a temperature of 100°C.

With inadequate viscosity a liquid layer of oil cannot be retained in the gaps, and as a result wear of the parts increases. Furthermore, the throwing of oil into the cylinders increases, as a result of which its expenditure grows, carbon formation is strengthened, the spark plugs become fouled which leads to interruptions in ignition and detonation, and to overheating and the destruction of the piston surface. At the same time contraction of the piston ring deteriorates, the compression drops, gases rush into the crankcase decreasing the engine power, the oil becomes contaminated, and corrosion of the bearings and sedimentation increases.

A too high viscosity of oil is also undesirable because it leads to an increase in the forces of friction, and therefore, during the normal operation of an engine it causes an increased loss of power. At a low temperature due to the high viscosity of the oil starting of the engine is hampered, and after starting the circulation is slowed down and spraying of the oil is impaired. Fresh oil does not enter the friction nodes in the proper time, and the oil found in the gaps is heated during the friction and it flows out. An oil deficiency arises along with increased wear or even seizing of the parts.

At the moments of starting and stopping the boundary film of oil must protect the friction nodes of the engine from dry friction, and also provide for the reliable operation of the reducer gears and other power transmissions where the formation of liquid friction is impossible. Therefore, the oil should possess a high lubricating capacity. Thus, the oil in an engine undergoes the effect of high temperatures and pressures, is found in close contact with various metals in the presence of the oxygen in the air. Under such conditions it should be very stable, in order to retain its properties for a long time and not to form large amounts of impurities in the form of carbon deposits, varnish, and slags.

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2. Brands of Oils for Piston Engines

For lubrication of aircraft piston engines the residual oils MS-14, MS-20, MS-20S and MK-22 (S — selective cleaning, K — acid-contact) are used. The basic physicochemical properties of these oils are given in Table 40.

Table 40.

Indicators	GOST 1013-49			GOST 9320-60 MS-20S
	MS-14	MS-20	MK-22	
Viscosity kinematic, cSt, at 100°C, not more than..................................	14	20	22	20
Ratio of the kinematic viscosity at 50°C to the kinematic viscosity at 100°C, not more than..................................	6,55	7,85	8,75	7,60
Coking capacity, %, not more than..............	0,45	0,30	0,70	0,45
Acidity, mg KOH per 1 g oil, not more than.....	0,25	0,05	0,10	0,05
Ash content, %, not more than.................	0,030	0,003	0,004	0,003
Content of:				
selective solvents...........................		Are absent		
water-soluble acids and alkalis..............		The same		
mechanical impurities........................		»		
water.......................................		»		
Flash temperature in a closed type instrument, °C, not below.................................	200	225	230	250
Difference in the flash temperatures in a closed and open type instrument, °C, not more than..	20	20	20	22
Thickening temperature, °C, not higher than	—30	—18	—14	—18
Color of a mixture: 15% oil and 85% colorless ligroin according to Duhosk, mm, not less than.	16	Type RA-7	15	10
Density at 20°C, not higher than................	0,890	0,893	0,905	0,895
Thermal oxidizing stability according to the method of paper at 250°C per min, not less than	20	17	35	17
Corrosiveness on plates of C2 lead according to GOST 3778-56, g/m², not more than.............	60	45	2	15
Coefficient of viscosity, not more than........	70	55	76	—
Sulfur content, % not more than................	—	—	—	1,0

As the experience of operation showed during work in engines the oil MS-20 and MK-22 are practically equivalent. In view of this when refueling an aircraft they can be mixed in any ratios.

Those distinctions of the physicochemical properties that exist between these oils (in the thickening temperature, acidic number, **coking** capacity, etc.) are important only from the point of view of controlling the conditional state of the fresh oil of each

brand. In process of operating in an engine they are far removed
from their initial values and are practically equalized.

All these oils have completely unsatisfactory low-temperature
properties which is evident by their thickening temperatures.
At external air temperatures below -5°C an engine cannot be started
because lubrication of the basic friction pairs is not provided
for due to the great viscosity of the oil. In winter to facilitate
the starting of an engine the oil is diluted with gasoline.
Gasoline for dilution (in the amount of up to 10% of the capacity
of the oil system) is taken from the fuel system of the aircraft
and is supplied under pressure to the manifold which connects the
oil tank with the oil pump of the engine. The valve for dilution
of the oil is opened when the engine is operating at low revolutions
before the engine completely stops. As a result of dilution the
thickening temperature of the oil drops approximately by 10°, and
starting proves to be possible at a temperature of -25-30°C. After
starting the engine the gasoline from diluted oil vaporizes and the
viscosity is reduced (Fig. 101). When the temperature of the air
is minus 25-30°C the oil must be poured from the oil system after
flights, and before starting be heated to 90-105°C.
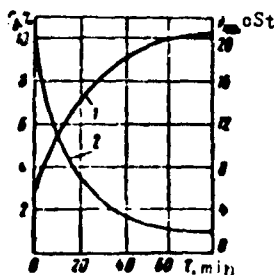
Fig. 101. Behavior of oil diluted with gasoline,
during starting of an engine: 1 — the change in
the viscosity; 2 — the change in the concentra-
tion of gasoline.

3. Change in the Properties of Oil During the Operation of a Piston Engine

In the process of the operation of an engine the oil found in
it changes its initial properties under the effect of a number of
factors characteristic for the given type of engine and the conditions
of its use.

Primarily the processes of oxidizing polymerization of the
hydrocarbons occurs in the oil, as a result of which in it the
products of oxidation (asphaltenes, resins, carboids, organic
acids, etc) accumulate in it. Studies showed that some substances
formed in the process of oxidation are inhibitors of the processes
of oxidation. The products of oxidizing polymerization precipitate
out from the oil in the form of a varnish film on the engine parts
and thereby decrease the catalytic effect of metals on the processes
of oxidation. All this leads to the fact that in general the
processes of oxidation of the working oil in the course of time
are slowed down, and the oil itself becomes stabler, i.e., more stable
against oxidation (Figs. 102, 103, 104, 105).
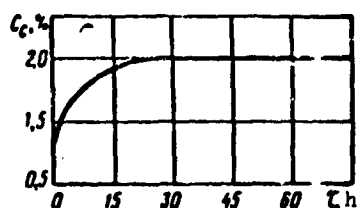
Fig. 102. Change in the content of resins in
the oil during the operation of a piston
engine.
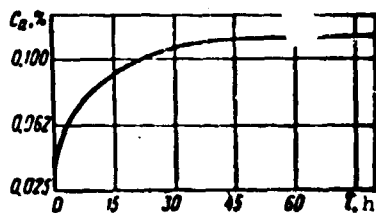
Fig. 103. Change in the content of asphaltenes
in the oil during the operation of a piston
engine.
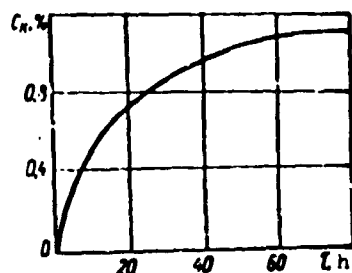
Fig. 104. Change in a content of carbenes and
carboids in the oil during the operation of a
piston engine.

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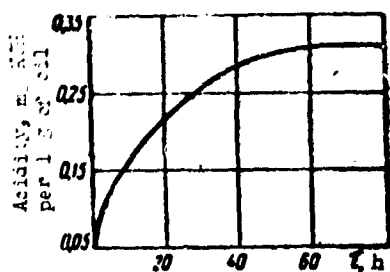
Fig. 105. Change in the acidity of the oil
during the operation of a piston engine.

Along with the products of oxidizing polymerization inorganic
impurities accumulate in the oil in the process of its operation
in the form of particles of wear, mechanical impurities which
entered the engine from the outside (dust particles), and also the
products of corrosion and incomplete combustion of the fuel and
oil.

Thus, the impurities which accumulate in the oil can be divided
into two parts — organic (products of oxidation) and inorganic
(mechanical impurities, the products of wear, corrosion, etc.).

C H A P T E R   XIV

TRANSMISSION, TECHNICAL AND INSTRUMENT OILS

1.   Transmission Oils

The lubricating materials used for lubricating the gears of
transmissions and universal joints refer to transmission oils. The
transfer of power from the engine to the rotor of a helicopter is
accomplished with the aid of transmissions.

The operating conditions of oil in transmission gears are
completely distinguished from the operating conditions of oil in
an engine. The friction node in a transmission is the toothed
engagement of worm, conical and hypoid gears. During the transfer
of large amounts of power, for example in the reduction gear of a
helicopter, extra high pressures are developed on the gear teeth
at a rather large rate of slip. On the narrow strip of contact of
the gears high temperatures are developed. Thus, the film of oil
found between the teeth of the gear at the moment of their contact,
undergoes the effect of extra high pressures, a high rate of slip,
and high temperatures. One of the basic requirements shown for
transmission oil is a maximum decrease in the wear and the complete
elimination of seizing of the gear tooth surfaces. Transmission
oils should possess high antiwear and antiseizing properties.

At the same time transmission oils should accomplish a number
of other functions, providing for reliable and long term operation
of transmissions. They should decrease the losses to friction,
provide a high efficiency of the transmission, remove heat from the

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provide a high efficiency of the transmission, remove heat from the contact zone, protect transmission parts from corrosion, not foam, and have sufficient stability.

The selection of oils satisfying these requirements is accomplished by selecting the oil and additives which give it the necessary properties.

Increased antiwear and antiseizing properties are given to transmission oils by adding chemically active substances. Under the very heavy operating conditions of transmission gears ordinary mineral oils, even with additive which improve their antiwear properties, are not suitable because they do not provide for minimum wear and do not eliminate seizing. Only the introduction of chemically active additives, containing sulfur, chlorine, phosphorus, etc., into oil gives positive results. The effect of such additives is that at high temperatures in the contact zone of the gear surfaces the additives are destroyed and they interact with the metal. In this case films of chlorides, sulfides, or phosphides of iron are formed on the surface of the metal. The latter melt at lower temperatures than the metals, and thereby protect the metals from seizing at the points of contact, and they decrease wear. Furthermore, because of the lamellar structure such films possess a low resistance to shift which provides for a decrease in the coefficient of friction.

With the correct selection of antiwear and antiseizing additives low wear of the transmission parts will be provided for within certain limits independent of the viscosity of the oil. At the same time the viscosity of transmission oils should be optimum because highly viscous oils which provide for a steadier boundary film and improve the airtightness of gaskets lead to considerable losses to friction, especially under low temperature conditions.

The requirement of high stability for transmission oils is comparatively easily to fulfill because the oils do not undergo the effect of high temperatures in a volume.

Oils containing resins which are unstable at high temperatures, high-molecular organic acids, sulfurous, and several other compounds, which possess a good lubricating capacity can operate in transmissions. Therefore, to lubricate transmissions, unpurified oils and even the resinous-asphalt product removed from engine oils during the selective cleaning of them and tar are used.

Presently, to lubricate the reducers and Cardan joints of helicopters hypoid oils are used which are a mixture of tar and a low viscosity distillate (spindle) with the addition of a depressing agent — additive which lowers the thickening temperature and improves the fluidity at low temperatures.

Hypoid oils contain 1.5-3.5% sulfur. They avert the seizing of metals well under high loads, but the oxidizing wear of the gear teeth will be somewhat increased. This is explained by the fact that the films formed in the friction process which avert seizing scale very easily and they are removed by the oil. The technical norms for hypoid oil are given below.

Technical norms for hypoid oil (GOST 4003-53)

Viscosity at 100°C, cSt	**20.5—32.4**
Thickening temperature, °C, not higher than...............	**—20**
Content of:	
sulfur, %, not less than....................................	**1.5**
water-soluble acids and alkalis...........................	**absent**
mechanical impurities, %, not more than..................	**0.1**
water..	**absent**
Test for corrosion.......................................	**passes**

2.   Technical and Instrument Oils

To lubricate separate nodes, units, and instruments special oils are used which most fully satisfy the operating requirements of the given node, unit, or instrument. Separate nodes, units, and

especially aircraft instruments operate under conditions of
increased moisture, intensive vibrations and shakings, and a very
wide range of temperatures (from -70 to 120°C). Under these
conditions the oil should have a low viscosity and retain a light
mobility at low temperatures because this will provide for sufficient
accuracy of the instrument readings. At the same time the oil should
not vaporize in a thin layer at elevated temperatures. The oil
should provide for the reliable protection of parts from corrosion
over a wide range of change in the external conditions (moisture,
temperature).

Vaseline instrument oil MVP is used presently as the technical
oil in aviation. Despite the fact that it is low viscosity, MVP
does not possess the necessary low-temperature characteristics.
The thickening temperature of the oil is -60°C, however already
at a temperature of -40°C it is practically incompetent because of
the rise in the viscosity (Fig. 106; The oil does not have a
good lubricating capacity.
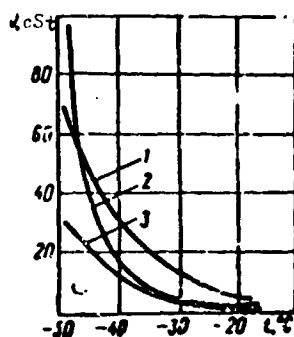
Fig. 106. Viscosity-temperature characteristics
of instrument oils: 1 — MVP; 2 — OKB-122-14; 3 —
OKB-122-4.

Organosilicon liquids and oils based on them posses the
necessary viscosity and low-temperature properties, and volatility.
The substantial deficiency of these liquids is their very poor
lubricating capacity. To improve the lubricating properties of
organosilicon liquids they are used in a mixture with mineral oils.

Today based on such mixtures the OKB-122 oils that possess low volatility, good low-temperature properties and high stability have been created. These oils are intended for lubricating instrument bearings and friction nodes, that operate at temperatures of from 120 to -60°C. The basic physicochemical properties of technical and instrument oils are given in Table 41.

Table 41. Technical norms for instrument oils

Indicators	GOST 1805-11 MVP	TU MKhP 4216-55			
		OKB-122-4	OKB-122-5	OKB-122-14	OKB-122-16
Viscosity at 50°C, cSt......	6,3—8,5	11,0—14,0	18,0—23,0	22,5—28,5	19,0—25,0
Flash temperature, °C, not below....................					
in an open type instrument	—	160	170	170	170
in a closed type instrument...............	120	—	—	—	—
Thickening temperature, °C, not higher than...........	—60	—70	—70	—70	—70
Ash content, in %, not more than....................	0,005	—	—	—	—
Content of water-soluble acids and alkalis..........			Absent		

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C H A P T E R   XV

CONSISTENT GREASES

Consistent greases are lubricating materials thickened by
special method to provide lubrication conservation, and packing of
those friction nodes and parts of an engine for which ordinary
liquid lubricants cannot be used due to specific operating conditions
and the design of the friction node.

Consistent greases — plastic colloidal systems, which are
substantially distinguished in their nature and properties from
liquid oils. They are obtained by introducing thickeners and other
components into liquid oils giving them special properties (additives,
fillers, stabilizers, etc.).

Consistent greases are used to decrease friction and wear in
various mechanisms and friction nodes (antifriction), to protect
metal parts from corrosion (protective), to hermetically seal
various joints, gaskets, and valves (sealing).

1.   The Structure of Consistent Greases

The greases are dispersed (colloidal) systems, consisting,
as a rule, of two phases: liquid and solid. The liquid phase of the
greases (mineral oil, synthetic liquid, etc.) is called the
dispersion medium. The thickener put into the oil forms the solid

dispersed phase. Liquid oil in greases is retained in cells of
the structure frame formed by the particles of the dispersed phase,
mainly under the effect of capillary forces. Figure 107 shows
the structures of various consistent greases. The character and
structure of the structural frame in many respects determines the
mechanical and operational properties of the greases. The capacity
of the frame to be elastically transformed without failure at small
loads gives a plasticity to the greases, which allows them to be
used in nonhermetic the friction nodes.
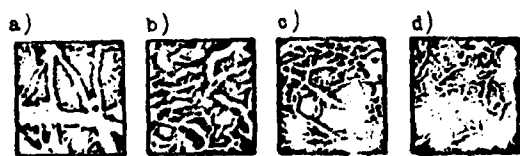
Fig. 107. Structure of consistent
greases magnified 10,000 times): a)
barium soap; b) strontium soap; c)
lithium soap; d) calcium soap.

The structure of the greases is determined by their composition,
the technology of manufacture, the mechanical treatment, and by
other factors. A main role here is played by the nature of the
thickener. The structure of the greases also depends on the chemical
composition and the properties of the liquid phase. The surface-
active substances added in the form of additives, such as water,
glycerine, free fatty acids, and others have a large effect
on the structure. Of the technological factors, the rate of cooling
and the mechanical treatment show up first of all.

The structure of consistent greases is usually studied only
at very large magnifications (on electronic microscopes), which
is explained extremely by the small size of the particles which
form the dispersed phase of the greases. Presently the structure
of almost all types of greases has been studied.

The overwhelming majority of greases, thickened with soaps of
the highest fatty acids (soap greases), has a micro- and submicro-
fibrous structure with fibers which are characterized by a large
ratio of length to diameter (10:1 and more, Fig. 108).
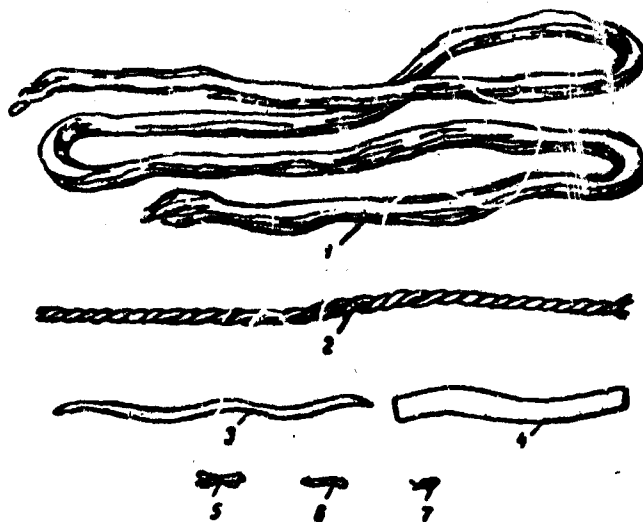
Fig. 108. Relative sizes of particles of the dispersed phase of consistent greases and microorganisms: 1 -- sodium grease (1 × × 100 microns); 2 — bacillus of recurrent typhus (0.35 × 15 microns); 4 — *Bacillus anthracis* (1.1 × 7 microns); 5 -- litmium grease (0.2 × × 2 microns); 6 -- sodium grease (0.15 × 1.5 microns); 7 — calcium grease (0.1 × 1 micron).

The soap fibers (micelles) consist of aggregated molecules of soaps. There can be several tens of molecules in one micelle.

By intertwining and combining among themselves, the soap fibers form the three-dimensional structural frame of the grease (see Fig. 107). The greases, in which the thickeners are solid hydrocarbons (hydrocarbon greases), are close to soap greases according to the thin structure. Paraffin or ceresin crystallizing in oil, form a three-dimensional grid, piercing the whole thickness of the grease.

2. Basic Types of Consistent Greases and Their Composition

By composition all consistent greases can be broken down into several basic groups depending on the type of oils they were prepared from and on the type of thickeners, put into them. Since the greatest effect on the properties of the greases is shown by the thickener, then the classification of greases is usually accomplished

according to the type of thickener. The following four groups of greases exist: soap, hydrocarbon, inorganic, and organic.

The most widely used are the greases of the first two groups. However recently inorganic and organic greases have been more and more widely distributed because they upon mastering their technology can more completely satisfy the operational requirements, especially for friction nodes, that operate at very large rates of a rotation, in a vacuum, and without the prolonged replacement of the grease.

Soap greases. The salts of the highest fatty acids serve as thickeners in soap lubricants. The soaps used in the production of consistent greases can be manufactured both from vegetable and animal fats consisting of the highest fatty acids, and their glycerines, and from the fatty acids obtained synthetically. Correspondingly, the consistent greases are also subdivided into fatty and synthetic.

Fatty acids refer to carbonaceous acids R—COOH, where R — the radical of an aliphatic (fatty) hydrocarbon (an alkane, alkene or alkadiene). The glycerides, i.e., the complex ester triatomic alcohol-glycerin $C_3H_5(OH)_3$ and the fatty acids R—COOH, are formed according to the following diagram:

$$C_3N_6(OH)_3 + 3(R-COOH) \rightleftarrows C_3H_5(R-COO)_3 + 3H_2O,$$

or in the developed form:

$$
\begin{array}{l}
\quad\quad\text{H} \\
\quad\quad | \\
\text{H--C--OH} + \text{R--COOH} \\
\quad\quad | \\
\text{H--C--OH} + \text{R--COOH} \\
\quad\quad | \\
\text{H--C--OH} + \text{R--COOH} \\
\quad\quad | \\
\quad\quad\text{H}
\end{array}
\left.\begin{array}{}\\ \\ \\ \\ \\ \\ \\ \end{array}\right\}
\rightleftarrows
\begin{array}{l}
\quad\quad\text{H} \\
\quad\quad | \\
\text{H--C--OOCR} + \text{H}_2\text{O} \\
\quad\quad | \\
\text{H--C--OOCR} + \text{H}_2\text{O} \\
\quad\quad | \\
\text{H--C--OOCR} + \text{H}_2\text{O} \\
\quad\quad | \\
\quad\quad\text{H}
\end{array}
$$

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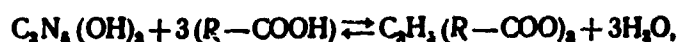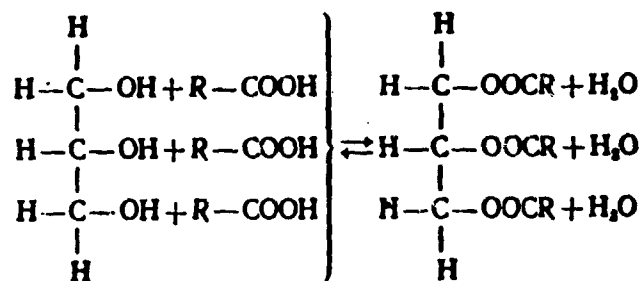
Reactions of this type, as is known, are called esterification and are reversable. Under the effect of a number of factors (hydrolysis, for example) and alkalis the glycerides are split into glycerine and free fatty acids. Under the effect of alkalis on glycerides the fatty acids are not in a free state, but in the form of salts, called soaps, and the reaction receives the name of saponification. For example:

$$C_3H_5(R-COO)_3 + 3NaOH \rightarrow 3(R-COONa) + C_3H_5(OH)_3.$$
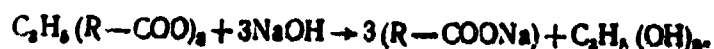
The free fatty acids also saponify as

$$R-COOH + NaOH \rightarrow R-COONa + H_2O,$$

only in this case is water liberated.

Similar reactions also occur during the saponification of fatty substances and with other alkalis:

$$2C_3H_5(R-COO)_3 + 3Ca(OH)_2 \rightarrow 3(R-COO)_2 Ca + 2C_3H_5(OH)_3;$$
$$2(R-COOH) + Ca(OH)_2 \rightarrow (R-COO)_2 Ca + 2H_2O.$$
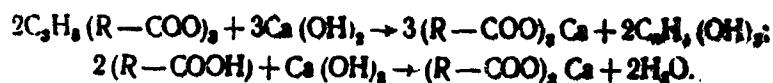
Various saturated and unsaturated fatty acids and their glycerides enter the composition of vegetable and animals fats, moreover, the limited acids and their glycerides perdominate in solid (specifically, in animal) fats and the unlimited — in liquid — (vegetable). The presence in fats of unlimited compounds leads to obtaining a less chemically stable thickener, inclined to oxidation and decomposition.

In recent years to replace the vegetable fats synthetic fatty acids have received wide application in the boiling of soaps — the thickeners of consistent greases. Synthetic fatty acids saponify in the same manner as natural acids.

Depending on which alkalis were used during the saponification of natural or synthetic fatty substances to obtain the thickeners, the consistent greases are subdivided into sodium, calcium, aluminum, zinc, litmium, barium, etc.

Consistent greases on a combined base are also used as, for instance, calcium-sodium and others. Many properties of the consistent greases depend to a considerable degree on the type of thickener. *Calcium greases* are distinguished by their good water resistance and therefore are widely used in friction nodes that operate in contact with water. In a majority of calcium greases the stabilizer of the structure is water. According to modern concepts the water hydrates in these greases into calcium soaps. Such crystal hydrates have the characteristic form of a double-coil rope, being easily distinguished under an electronic microscope, and they possess a high thickening capacity. The amount of water necessary for stabilization comprises approximately 3-4% of the weight of the soap.

With a loss by the calcium grease of water (dehydration) decay of the structure occurs which is evident from Fig. 109.
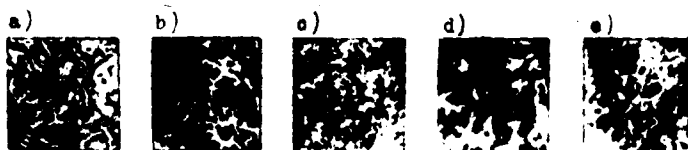
Fig. 109. Change in the structure of a calcium grease at its dehydration (desiccation): a) initial hydrated calcium grease; b), c), d) stages of dehydration; e) the dehydrated calcium grease.

Calcium greases can be used at temperatures up to +100°C. At a higher temperature a change in the mechanical properties of the grease occurs — it liquidifies and flows out the friction node. Typical representatives of calcium greases are the greases used as mass purpose greases.

Sodium greases are used at elevated temperatures because the high melting temperatures of sodium soap allow it to retain its mechanical properties up to temperatures of 110-200°C. High-temperature greases are prepared from highly viscous residual oils. Greases especially stable with respect to thermal pressures can be made from synthetic fatty acids. Sodium greases intended for use at low temperatures are prepared from low viscosity oils with good low-temperature properties.

Sodium greases cannot be used under conditions of direct contact with water because sodium soaps dissolve well in water.

Calcium-sodium greases. When sodium consistent greases cannot be used as a result of their unsatisfactory moisture resistance, and calcium because of the insufficiently high melting temperature, calcium-sodium greases are used. These greases, according to the melting temperatures and moisture resistance, occupy an intermediate position between calcium and sodium greases.

Lithium-greases can be used up to temperatures of 120-150°C because lithium soaps have high melting temperatures. At the same time lithium greases have good viscosity-temperature characteristics and are successfully used at low temperatures. This is explained by the fact that lighium soaps possess a high thickening capacity and this makes it possible to obtain stable greases when low viscosity oils are thickened with a small quantity of soap. Lithium soaps dissolve very badly in water, which makes it possible to use them under conditions of increased moisture. The successful combination of a good thickening capacity, high melting temperature, and the practical insolubility of lithium soaps in water makes lithium greases one of the promising types of lubricating materials.

Hydrocarbon greases are prepared by thickening highly viscous liquid mineral oils with solid hydrocarbons — with ceresins and paraffins. Hydrocarbon greases have such valuable qualities as

high chemical stability and water resistance which makes them
high-quality protective greases. The capacity of hydrocarbon greases
to retain their structures and property after melting and subsequent
cooling plays a large role. This makes it possible to apply these
greases to protective metal parts in the molten state.

In certain cases hydrocarbon greases are used as antifriction
greases but for friction nodes that operate under conditions of low
temperatures and small loads.

Inorganic greases — this is the product of thickening liquid
oils (mineral or synthetic) with inorganic materials. Inorganic
greases probably will be promising for such operating conditions
in which soap, but the more so hydrocarbons cannot operate, i.e.,
at temperatures of 400-500°C and above, in a deep vacuum, in an
aggressive medium, etc.

Presently a large number of inorganic thickeners is already
known: silica gel, molybdenum disulfide, silicates, sulfides,
oxides, hydroxides of metals, carbon black, graphite, mica, etc.
In order that the grease with the inorganic thickeners, be able to
operate at high temperatures, it is necessary to have a qualitative
liquid component. Liquid oil, whose efficiency is retained at high
temperatures, can be obtained only by a synthetic method. Therefore
inorganic greases are prepared, as a rule, from high-quality
synthetic oils.

Organic greases. Several organic substances were suggested as
thickeners for consistent greases such as phthalocyanine compounds,
derived urea, heterocyclic compounds, and others. Organic greases
have very good operational properties and can be used universally
for various mechanisms and conditions of use.

Greases thickened with aryl-derived urea possesses very good
operational properties. These greases have a good thermal and
chemical stability.

At the present time organic greases have still not obtained mass application because of the high cost of the organic thickeners.

Liquid media for greases. High-quality greases can be obtained only when using liquid oils which possess the necessary operational properties to produce them. The oils being used for this should have a gently sloping viscosity-temperature characteristi), **low** volatility, and good chemical stability over a wide range of temperatures. Presently commercial mineral oils, selected according to the level of viscosity depending on the designation of the grease, are used in the production of **greases**.

Special synthetic liquids should be considered as very promising in the development as a thickening medium, especially, polysiloxanes, diesters, polyglycols, fluorocarbons, and other organic liquids. In principle it is possible to synthesize a liquid with any previously assigned properties, including those extremely necessary, as a gently sloping viscosity-temperature characteristic, chemical and mechanized stability, etc. It is now possible to speak about the successful work in creating and using greases based on silicone liquids, which are efficient in a temperature range of from -80 to +300°C.

Additives for greases. A grease is a very complex in composition type of lubricating material. Some types of greases contain more than ten components. Apart from liquid oil and a thickener which make up the base of the greases, they contain small quantities of products which remain in them after manufacture. This can be glycerine, which is similar to the product of the reaction of the saponification of fats with an alkali in the production of soap greases. It is possible to assume that glycerin is not simply mechanically maintained in a prepared grease, but it substantially influences the formation of its structure.

Sometimes surplus free alkali remains in small quantities in grease during its manufacture. The free alkali neutralizes the products of oxidation, which are formed in the grease during its use. In some greases water is present, which plays an important role in the formation of the structure of the greases (water calcium greases). Additives of a special designation are frequently added to greases. To improve the antiwear and antiseizing properties of some types of greases, graphite, mica, molybdenum disulfide, compounds of sulfur, chlorine, and phosphorus are put into them. Antioxidant and anticorrosion additives are put into greases.

Also additives which improve their water resistance, step up the colloidal capacity, improve the mechanical characteristics and other properties are put into greases.

3. Brief Information on the Technology of Producing Consistent Greases

The production of soap greases can be origanized both with the use of prepared soaps, and by obtaining soap in the process of boiling.

The production of greases from prepared soaps is reduced to the dispersion of the prepared soap in liquid oil with the subsequent formation during cooling process of the necessary structure of the grease.

Prepared soap and a small quantity of oil is loaded into digester. After heating to the necessary temperature, dehydration of the soap base, swelling and dissolving the soap in oil the remaining quantity of oil is supplied to the digester. Dispersion of the soap in the oil is accomplished with intensive mixing. Additives are added to the grease, as a rule, after dissolving the soap in the oil. After boiling, the grease is either poured

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directly from the digester into a can, or is cooled preliminarily and subjected to mechanical treatment to give it the necessary structure.

In continuous action devices, a suspension of dry soap in oil is prepared in a special mixer. The suspension is pumped by a pump through a heater, where the soap dissolves in the oil and it goes further through a cooling apparatus, where the necessary structure of the grease is formed.

The production of greases by obtaining soap in the process of melting is reduced to the following operations. Into a digester-mixer is put the entire load of saponifiable fat or fatty acids and the required according to calculation amount of hydroxides of the appropriate metal. After this part of the mineral oil is put into the digester and by mixing and heating the saponification of the fat or neutralization of the fatty acids is accomplished. After the removal of surplus water, the remainder of the mineral oil is put into the digester. Subsequently, the process of producing the grease is accomplished in the same manner as with prepared soaps.

The line diagram of the production of hydrocarbon greases is very simple. It is reduced to mixing the molten thickener (ceresin, paraffin) with the oil and cooling the mixture.

Mineral oil is pumped into a digester and after heating a previously melted thickener is added to it. If necessary, at this time various additives are put into the digester. For uniform distribution of the components intensive mixing of the mixture is accomlished. After mixing it is cooled and packed into a can. Sometimes the grease is subjected to additional mechanical treatment.

The production of inorganic and organic greases is reduced to the dispersion of the thickener, obtained separately by chemical means, in the oil. The dispersion of the thickener in the oil is accomplished on the high production continuously acting colloidal

mills, paint grinders and others. Mixing the thickener with the
oil can be accomplished both at normal, and at elevated temperatures.

4. Properties of Greases and Their Control

The mechanical properties of greases, i.e., their behavior
under the effect of external forces, determine the possibility of
applying these greases in this or that friction node. Will the
grease flow out of the friction nodes; what forces must be spent
to overcome the internal friction of the grease during work; how
large will the wear of the parts of the mechanism being lubricated
be — all these and many other characteristics of the grease are
determined basically by their mechanical properties.

First of all the elastic-plastic and the strength properties
of the greases should be examined. These properties are manifested
in the fact that at small loads the greases retain internal structure
and are elastically deformed in the same manner as solid bodies.
With an increase in the load the structural frame of the grease
is destroyed, it loses the properties of a solid body and begins to
flow in the same manner as a viscous liquid.

Therefore, the grease has a limit of strength to shear. The
limit of strength determines the capacity of the greases to retain
their form under the pressure of applied loads, i.e., the capacity
to be retained in nonhermetic friction nodes, not to be thrown from
moving parts, not to flow off of vertical surfaces, etc.

In the work range of temperatures the limit of strength of a
majority of greases constitutes from 1 to 30 g/cm^2. To determine
the limit of strength of greases there exists and instrument, the
K-2 plastometer created by K. I. Klimov. A diagram of the K-2
plastometer is given in Fig. 110. Determination of the limit of
strength of greases according to this method (GOST 7143-54) is based
on fixing the minimum pressure that causes the shear of the grease
in capillary 2 of the K-2 plastomer. Upon heating of reservoir 6,

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due to the thermal expansion of a liquid the pressures in the hermetically sealed system of the instrument rise. At the moment of shear of the column of grease due to the increase in the volume of the system the pressure falls. The maximum pressure achieved during the determination, fixed by the manometer, corresponds to the limit of strength of the grease.
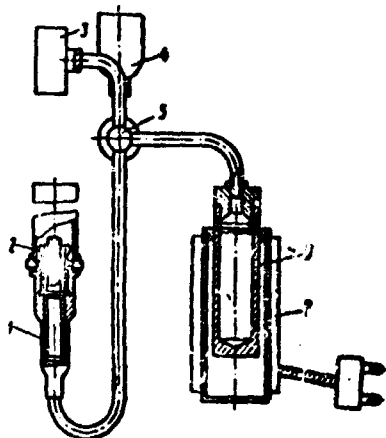
Fig. 110. Diagram of the K-2 plastomer: 1 — the capillary housing; 2 — capillary; 3 — manometer; 4 — funnel; 5 — valve; 6 — oil reservoir; 7 — electric heater.

Since with an increase in the load higher than of the limit of strength the grease flows in the same manner as a liquid, then one of the most important characteristics of greases is their viscous properties. A study on the viscous properties of greases was accomplished by G. V. Vinogradov, V. P. Pavlov, M. D. Bezborod'ko, A. A. Konstantinov, Arveson, and others. Consistent greases have a structure formed by the components entering their composition. This structure determines one of the characteristic properties of greases — the presence of structural viscosity which depends upon the gradient of the rate of deformation. This means that the viscosity of the consistent greases is very large with a small gradient of the rate of deformation and with an increase, it decreases to a certain minimum quantity. With a further increase in the gradient of the rate the viscosity of the grease no longer changes and the consistent grease begins to act like a Newtonian liquid (Fig. 111).

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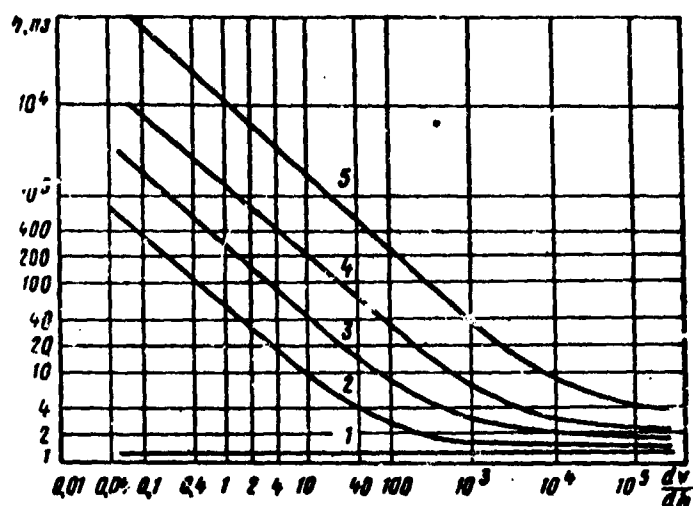
Fig. 111. Dependence between the viscosity of a grease and the rate gradient: 1 — mineral oil; 2 — calcium consistent grease prepared from the same oil containing 3% soap; 3 — the same, with 6.1% soap; 4 — the same, with 10.1% soap; 5 — the same, with 18.8% soap.
Designation: пз = poise.

The intensity of the change in the viscosity with the change in the gradient of the rate of deformation characterizes the viscous properties of the greases. The viscosity-rate characteristic which determines this dependence can be expressed by the ratio to the viscosity of the grease at two various gradients of the rate of deformation (the temperature is constant). Greases which possess a large dependence of the viscosity on the gradient of the rate of deformation (a steeper curve) are considered better.

At a constant gradient of the rate of deformation the viscosity of a grease changes with a change in the temperature. Therefore, the second characteristic of the viscous properties of a grease is their viscosity-temperature characteristic (Fig. 112). The viscosity-temperature characteristic of greases deteriorates with an increase in the gradient of the rate of deformation, at which it was determined.

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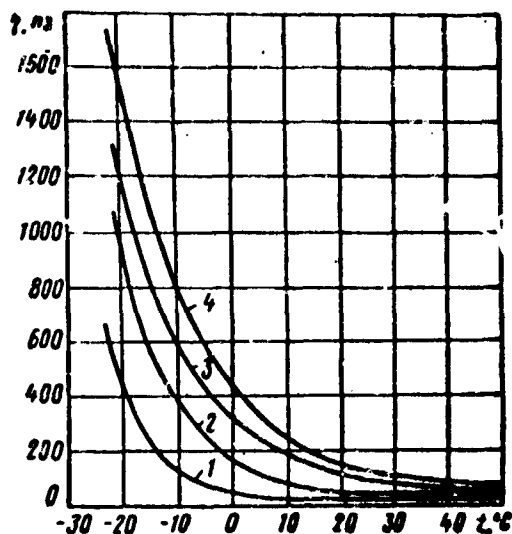
Fig. 112. Viscosity-temperature curves of consistent greases (at a rate gradient of 400 s-1): 1 — US-1 gun grease; 2 — US-2 gun grease; 3, 4 — synthetic experimental cup grease from evolved acids.

To determine the viscous properties of consistent greases the AKV-2 constant expenditure capillary viscosimeter was created (GOST 7163-54, author A. A. Konstantinov). A diagram of the viscosimeter is given in Fig. 113. The grease is pushed out by rod 4 from chamber 5 through capillary 6. The extrusion of the grease through the capilla.y is accomplished with the aid of the previously compressed spring 1. With a completely compressed spring the discharge takes place under large pressure at a high rate; in proportion to the movement of the rod the pressure in the chamber and the rate of shear of the grease in the capillary fall. In this way a variable rate of discharge (the gradient of the rate of shear) is attained.

To maintain a constant temperature, a liquid circulates through housing 7. A pencil 3, connected to rod 4, with the movement of the latter draws on the paper fixed to drum 2 the curve, according to which at determined points it is possible to find the rate of movement of the rod v cm/s and the pressure exerted by it on the grease P kgf/cm^2. To get the complete viscosity characteristic 10-15 g of the tested grease is required. The viscosimeter makes it possible to conveniently evaluate the viscosity of the greases over a range of gradients of the rate of shear of from 0.1 to 100,000 s^{-1}, viscosities from 10 to 100,000 poise at temperatures

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of from -60 to 130°C. The **viscosity** characteristics of a number of greases determined on the AKV-2 instrument, are given in Fig. 114.
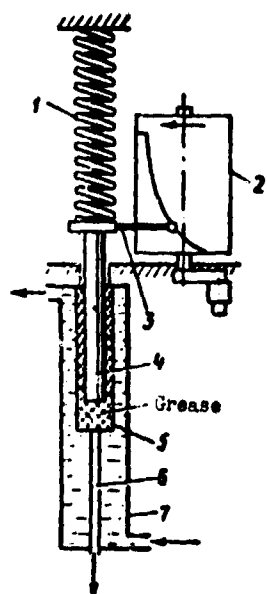
Fig. 113.   Diagram of the AKV-2 viscosimeter.
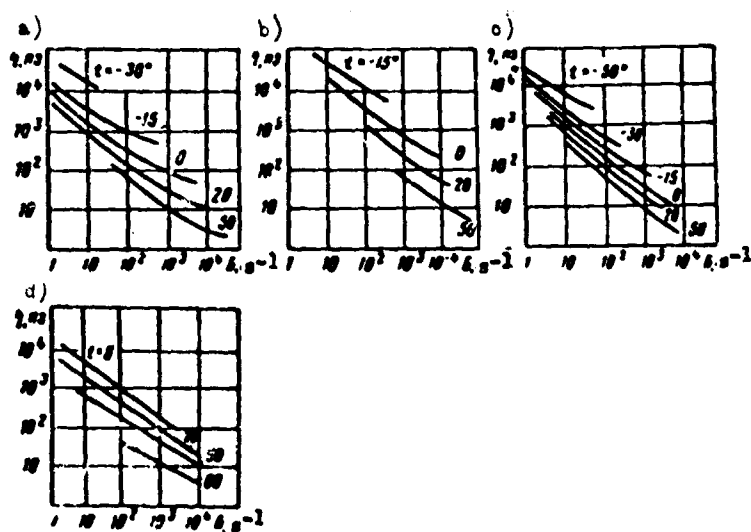
Fig. 114.   Viscosity characteristics of consistent greases: a) fatty grease; b) synthetic grease; c) TsIATIM-201; d) 1-13 grease.

The methods of determining the viscosity properties of greases were developed and standardized comparatively recently. The most widely used for evaluating the mechanical properties of consistent greases is the penetration method according to GOST 5346-50. It is based on determining the depth that a cone of a given weight will sink into grease in 5 s. A diagram of the penetrometer is given in Fig. 115.
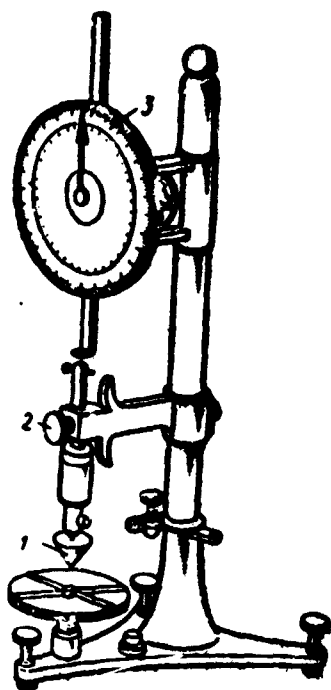
Fig. 115. Diagram of a penetrometer; 1 — housing; 2 — cone stop button; 3 — indicator.

The depth of sinking, expressed in tenth fractions of a millimeter, is called the penetration number.

Penetration numbers — the especially empirical values which do not possess a physical meaning and that do not determine the operational properties of greases. Greases which have completely different properties, can have the equal penetration numbers.

Consistent greases, as colloidal systems, possess thixotropic properties. During mixing and other mechanized pressures their initial structure is destroyed; after a more or less prolonged rest

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it is restored. However with a thixotropic reduction the mechanical properties of consistent greases by far do not always attain the initial values present before the breakdown of the structure. This is possible to explain by the fact that all bonds of the structure frame of the consistent grease which were destroyed under mechanical pressure, can be completely restored.

Determining the thixotropic properties of consistent greases has an important value for evaluating the operational qualities because the thixotropic properties show how deeply the properties of these greases change under mechanical pressures and how rapidly and fully these features are restored.

One of the important characteristics of greases is the change in their properties under the effect of temperature. With an increase in the temperature naturally such properties as viscosity, the limit of strength, penetration, etc., change, and upon reaching a determined temperature the grease begins to melt. The melting of consistent greases which is a consequence of the failure of its structure, occurs over a relatively wide temperature range. Evaluation of the temperature resistance of consistent greases is accomplished from the temperature of dripping, i.e., the temperature, at which the first drop of the melted grease falls from the opening of cap 1 of a special instrument (Fig. 116), placed in a gradually heated glass test tube – air bath (GOST 6793-53). It is tentatively considered that greases can be used at temperatures 15-20° lower than their temperature of dripping. The temperature of dripping depends on the nature of the thickener and the oil.

Consistent greases being used in friction nodes should have good antiwear and antiseizing properties. Determination of the antiwear and antiseizing properties of greases is the same as for lubricating oils, accomplished today on various friction machines.
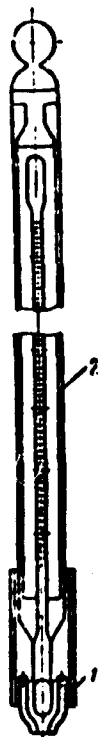
Fig. 116. Diagram of an instrument for determining the temperature of dripping of grease: 1 — cap; 2 — thermometer.

Physicochemical properties. Along with the mechanical characteristics a number of the physicochemical properties of greases, which determine their behavior under operational conditions has a very important value. Greases should be stable, i.e., retain their structure and properties over a prolonged period, both under conditions of storage, and during their use. The stability of a grease is evaluated according to the chemical and colloidal stability.

The chemical stability is called resistance of the grease to oxidation with the oxygen of the air during storage and under conditions of use. Upon the oxidation of greases products which are dangerous in the corrosion relationship, accumulate in them. Furthermore, oxidation of the grease can cause a change in its mechanical properties (viscosity, limit of strength, etc.).

Evaluation of the chemical stability is accomplished according to GOST 5734-53. This method consists of oxidizing the grease with oxygen in a special bomb at elevated pressures and temperature. As a result of heating the pressure in the bomb increases from the beginning, then it is held constant until the absorption of oxygen

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by the grease during its oxidation begins. The time from the moment the bomb is placed into the thermostat until the beginning of the drop in pressure in it as a result of the oxidation of the grease is considered as the induction period. After oxidation in the bomb the acid number of the grease is determined. The longer the induction period of the grease and than less the acid number rose in comparison with the initial one, the higher its chemical stability. It ought to be noted, that this method is very complex and has a series substantial deficiencies. However another simpler and more reliable method has not yet been developed.

The colloidal stability is called the capacity of the greases to resist the separation of oil from them (syneresis) during storage under conditions of use.

Syneresis is a consequence of the inadequate colloidal stability of a grease under conditions of temperature and mechanical pressures. With rather large quantities of separated out oil (15-20%) the properties of the grease change considerably and it cannot be used for what it was designated. Syneresis represents the greatest danger for greases prepared of low viscosity oils and containing small quantities of a thickener.

One of the methods of evaluating the colloidal stability of consistent greases is to test the grease on a KSA instrument (Klimov, Sinitsyn, Aleyeva) according to GOST 7142-54 (Fig. 117). In this instrument the tested consistent grease 2 is placed under piston 3 in small cylinder 6 mounted on a pack of paper filters 1. A rod with load 4 on it presses through ball 5 to the piston. The colloidal stability of the grease is evaluated in accordance with the quantity of oil (in % by weight) pressed out of it during the test after 30 min.
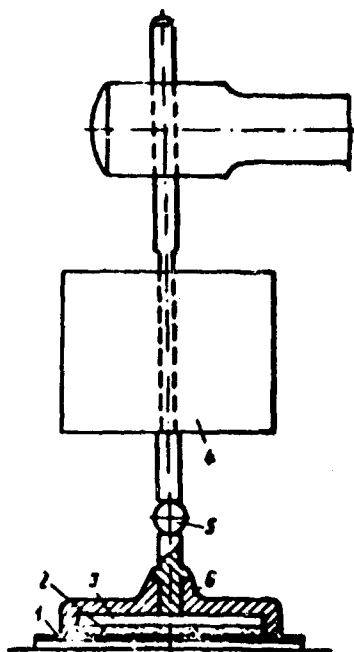
Fig. 117. Diagram of the KSA instrument: 1 — pack of paper filters; 2 — consistent grease; 3 — piston; 4 — load; 5 — ball; 6 — cylinder.

Consistent greases can contain organic acids not only as a result of oxidation, but also as a result of the incomplete saponification of the basic fatty substances. In the case of the introduction during melting of the soap of a surplus of alkali the greases can contain a free alkali. A check of consistent greases for their lack of corrosion on metals is provided by acting standards.

Tests are conducted by holding preliminarily polished metal plated (steel, copper, lead, and others) in a grease for an assigned time. Traces of corrosion should not appear on the plates. The test is conducted at various temperatures and different holding. Besides the check for the absence of corrosion of the metal plates in the consistent greases, the content of free organic acids or alkalis is determined. An increased content of free organic acids and alkalis not only causes corrosion of the metals, but also substantially worsens the colloidal stability and the limit of strength.

The content of free acids or alkalis is determined by extracting them from the grease by a water alcohol solution with subsequent titration.

The water contained in them has a substantial effect on the operational properties of consistent greases. In some greases (calcium) water is one of the components of the structure of the grease, in other greases (sodium) only a very small quantity of water is allowed, and in the greases manufactured of nonsoap thickeners, the presence of water is not permissible. Quantitative determination of the water in greases is accomplished with an instrument, the diagram of which is given in Fig. 118. A quantity of 20-25 g of the grease are placed into flask 1 of the instrument, 150 ml of a solvent (gasoline or ligroin) are poured into it and the flask is heated driving the water from the grease; the water accumulates in the graduated part of trap 2 (GOST 1044-41).
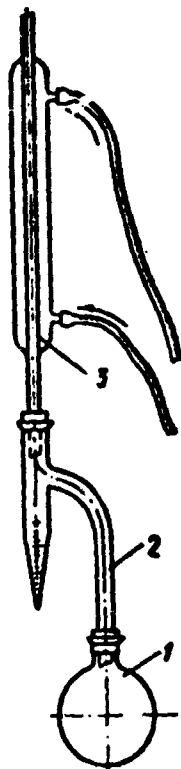
Fig. 118. Diagram of the instrument for determining the amount of water in greases: 1 — flask; 2 — trap; 3 — condenser.

Mechanical impurities which cause an abrasive effect are not allowed in greases. To determine the mechanical impurities in a grease a determined sample of it is dissolved and then filtered (GOST 1036-50). There also exists a method with the preliminary decomposition of the grease by hydrochloric acid (GOST 6479-53).

5. Brands of Greases Used in Aviation and Their Characteristics

Antifriction, preventive, and sealing consistent greases are used in aviation technology.

Antifriction greases

TsIATIM-201 (UTVMA — universal refractory moisture-resistant frost-resistant activated) is prepared by thickening vaseline instrument oil MVP with lithium soap and it contains a stabilizing additive. The range of working temperatures of this grease is from -60 to 140-150°C. The grease is unfit for friction nodes where the working temperatures can be above 160-180°C, and also for friction nodes with very large specific loads. In connection with the small concentration of thickener and the low viscosity of the oil in it the TsIATIM-201 grease under conditions of prolonged storage at elevated temperatures is inclined to syneresis. Therefore it is stored in a cool place in a shallow can, in order that the oil does not squeeze itself out under the pressure of the overlying layers of grease.

A variety of the TsIATIM-201 grease are the greases: TsIATIM-202, prepared from a more viscous mineral oil, in connection with which it has high temperature of dripping, and TsIATIM-203, which contains antiwear and antiseizing additives which makes it possible to use it for friction nodes with elevated specific pressure (the cyclic pitch control nodes of helicopters).

The NK-50 (ST-aircraft refractory) is the product of thickening MK-22 oil with sodium soap. Colloidal graphite is added to it to increase the antiwear and antiseizing properties. The grease is used in friction nodes, where large specific loads and elevated temperatures are possible: for the landing gear wheel bearings of aircraft and helicopters, the splined joints of the sleeves of propellers with the engine shaft, the valve mechanism for piston engines, and others.

The deficiency of NK-50 grease is the fact that at elevated moisture it swells and slips off of the parts, but at low temperatures it hardens and it splits off. In connection with this it is necessary to thoroughly examine the nodes and to renew or replace the grease on time.

Graphite grease is cylinder oil, thickened with 12% calcium soap, prepared of synthetic fatty acids. It contains 10% graphite, is waterproof, and is used for lubricating rough, highly stressed friction nodes.

The OKB-122-7 grease is prepared by thickening a mixture of ethyl polysiloxane liquid and of MS-14 mineral oil with lithium separate and ceresin. It is intended for friction pairs that operate at small loads, but for a prolonged time without replacement of the grease under temperature conditions of from -70 to +120°C; is also used for lubricating the magneto bearings of piston engines.

Grease No. 6 — organosilicon, is used for lubricating the surfaces of rubber products which rub on metal; it is used in the penumatic systems of aircraft.

The technical norms for antifriction greases are given in Table 42.

Table 42. Technical norms for antifraction greases.

Indicators	TsIATIM-201 (GOST 6267—52)	TsIATIM-203 (TU-MNP 340—50)	NK-50 (GOST 5572—50)	Graphite (GOST 3333—55)
Temperature of dripping, ^{o}C, not below......	170	145	200	77
Number of penetration: at 25°C........	270—320	235—300	170—225	250
" -60°C........	50	25	—	—
Test for corrosion........		Passes		
Liberation of oil from a grease after 50 h, %, not more than......				
at 60°C........	4	—	—	—
at 100°C........	—	5	—	—
Content of free sulfur, %, not more than........	0,1	0,1	0,15	—
Content of mechanical impurities..		Absent		
" " water, % not more than	Absent	—	0,3	3,0
" " sulfur, %, not more than	—	0,2	—	—
Ash content, %, not more than	—	—	7,0	—

Protective greases

The TsIATIM 217-15, technical vaseline, and gun grease are used as protective greases on aircraft, helicopters, and engines. The technical norms for these greases are given in Table 43.

Table 43. Technical norms for protective greases.

Indicators	TsIATIM-217-15, (VTU 627—55)	Gun grease (GOST 3005—51)	Technical vaseline VTU 782—53
External form........		Uniform ointment	
Color........	Dark-brown	From light-to dark-brown	
Viscosity, cSt, at a temperature of:			
50°C........	100	—	—
60°C, not less than........	—	40	20
100°C........	15—22	—	—
Content of free alkalis, %, not more than........	0,1	—	—
Water content........		Absent	
Content of mechanical impurities, %, not more than........	Absent	0,07	0,03
Temperature of thickening, °C, not higher than........	—10	—	—
Test for corrosion........		Passes	
Temperature of dripping, °C, not below........	—	50	54
Acid number, mg KOH per 1 g of grease, not more than........	—	0,30	0,38

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Sealing greases

The following greases are used as lubricants for packing various joints: BU-gasoline resistant for the hermetic sealing of valves and the threaded joints of the fuel and oil systems of aircraft and engines; MGS — for the hermetic sealing of joints, gaskets, threads, and valves of the air, alcohol, glycerin, and water systems on aircraft (Table 44).

Table 44. Technical norms for sealing greases

Indicators	BU (GOST 7171-54)	MGS (TU MNP 351-53)
Color and external form............	Uniform mass of a light-brown color	Vaseline-like mass of a gray color
Temperature of dripping, °C, not below...............................	55	110
Number of penetrations at 25°C......	130—200	260—330
Test for corrosion...................	Passes	—
Content of mechanical impurities, insoluble in hydrochloric acid, %, not more than......................	—	0.5
Water content, %, not more than.....	0.3—2.0	Traces
Solubility in a mixture of 15% benzene and 85% gasoline, %, not more then..............................	20	—

C H A P T E R XVI

SOLID LUBRICANTS

Despite the substantial improvement in the quality of liquid and consistent lubricants, they cannot provide for long-term and reliable work in many friction nodes of modern and especially perspective aircraft.

Under high and very low temperatures, in a vacuum, in contact with chemically active media liquid oils and consistent greases become barely effective as a result of a low thermal and physico-chemical stability.

Recently, solid lubricating materials, or solid lubricants have found wide application for friction nodes operating under complex conditions. The assortment of solid lubricants increases with each year and their area of use is enlarged. There are several hundreds of elements, chemical compounds, and compositions which possess the properties of solid lubricants. Solid lubricants receive an ever greater distribution in aviation technology. There is a large quantity of friction pairs in modern aircraft which are lubricated with solid lubricants.

1. Mechanism of the Lubricating Action of Solid Lubricants

According to the studies of Prof. I. V. Kragel'skiy it is possible to realize external friction between two metal surfaces if the following condition is observed:

$$\frac{h}{r} \geqslant \frac{1}{2}\left(1 - \frac{2\tau}{\sigma_\tau}\right),$$

where h – the depth of the introduction of unitary unevenness, mm; r – the radius of unevenness, mm; τ – the resistance to the shear of the bridge of adhesion, kg/mm^2; σ_τ – the limit of fluidity of the deformed material of the surfaces of friction, kg/mm^2.

From this inequality it is evident that external friction will be more steady, the less the tangential strength of the bridge of adhesion or the larger the limit of fluidity of the deformed material.

For example, at zero strength of a bridge ($\tau = 0$, the ideal lubricant) the relative introduction can reach 1/2. If $\tau = \sigma_T/2$ (the complete absence of lubricating films), then external friction is impossible even at zero introduction, i.e., at the smallest loads on the friction surfaces. In practice it is possible to consider $\tau = 0$ during the friction of metals under conditions of a very good boundary or fluid-dynamic lubricants, and $\tau = \sigma_T/2$ under the friction of metals in a vacuum, when not only the adsorbed films have been removed from the surface, but also the metal oxide films. In a vacuum there is not difference between external and internal friction in metals.

Thus, to realize external friction it is necessary to create a layer which possesses a small value τ and a value σ_s less than σ_s of the basic material on the friction surfaces. In other words, the required condition of external friction is the observance of the rule of the positive gradient of mechanical strength, according to which material should increase its strength deeply from the zone of contact (the rule of I. V. Kragel'skiy).

The positive gradient of the mechanical strength can be created by applying various lubricating films onto the surface. Solid lubricants possess the exact property to create a positive gradient of the mechanical strength at a small value of τ. The following are

used as solid lubricants at the present time: laminated solid lubricants (graphite, molybdenum disulfide, boron nitride, tungsten disulfide, etc.), thin metal films (tin, lead, bismuth, etc.), composition lubricants with polymeric binding, polymer and composite lubricants.

The lubricating effect of laminated and solid lubricants is explained mainly by their structure because the relative strength of the bond between atoms in various directions is strongly distinguished in them.

This is caused by the fact that in solid lubricants the distance between the atoms found in one layer differ considerably from the distances between the atoms found in different layers. For example, in the lattice of graphite the distance between the nearest atoms of carbon in a layer are equal to 1.42 Å, and the shortest distance between the atoms in parallel layers is equal to 3.44 Å.

In the structure of solid lubricants there are usually two types of bonds - very weak (van der Waals) between the layers and strong (covalent, metal) inside the layer. The presence of the considerably weaker forces of the bond between separate layers in comparison with the analogous forces inside the layers is mutual for all materials with a laminated structure.

During friction a shear of the layers of the solid lubricant occurs, in this case because of the weak van der Waals bonds between the layers the resistance to shear will be very small. The small resistance to shear between two crystallographic planes still is not a sufficient criterion to evaluate the lubricating capacity of a solid lubricant. The surfaces of slip of laminated crystals are flat and smooth or wavy and corrugated. For graphite flat (smooth) monatomic layers are characteristic, for molybdenum sulfides - flat three-layered packs, and for antimonite (Sb_2S_3) - zigzag dual chains. It is obvious that sliding in the crystal along flat and smooth surfaces is considerably easier than along uneven and wavy surfaces.

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One of the necessary properties, which provide for the good lubricating capacity of laminated solid lubricants is their high adhesion to metal surfaces. Minerals are known (for example, talc), that possess a laminated structure and flat sliding surfaces but that do not exhibit any lubricating capacity as a result of their weak adhesion to metal surfaces.

The solid lubricants which do not possess a laminated structure (metals, polymers, etc.), exhibit a lubricating effect as a result of the small resistance to shear of the adhesion bridges being formed. When applied in a thin layer to a metal surface, they create a positive gradient of mechanical strength of friction materials and thereby provide for steady external friction with small friction forces.

2. Laminated Solid Lubricants

The disulfide of molybdenum $\alpha \cdot MoS_2$ crystallizes in a hexagonal system. The atoms of molybdenum are located between two layers of sulfur atoms. The distance between the closest atoms of molybdenum and sulfur $a = 2.41$ Å, and the closest distance between the atoms of sulfur in parallel layers $c = 3$ Å. Natural molybdenum disulfide is obtained during the extraction of copper ores from by-products containing molybdenum.

The synthetic molybdenum disulfide also has a laminated type structure but either rhombohedral $\beta \cdot MoS_2$ with parameters $a = 3.15$ Å, $c = 18.38$ Å, or intermediate between $\alpha \cdot MoS_2$ and $\beta \cdot MoS_2$.

Basic properties of MoS_2

Specific weight..............................	4.8 g/cm^3
Mohs hardness................................	$1.0-1.5$
Temperature of the beginning of sublimation..................................	$450°C$
Melting point................................	$1185°C$
Coefficient of linear expansion over the temperature range 50-700°C.................	$7 \cdot 10^{-6}/1°C$
Thermal conductivity...................	$4.9 \cdot 10^{-3}$ kcal/cm·s·deg

Magnetic properties..................... diamagnetic
Chemical resistance................. dissolves in aqua
                                      regia, oxidizes in
                                      concentrated H_2O_4
                                      and HO_3
Luster...................................... metallic
Color........................... blue-gray to
                                  black

In air MoS_2 oxidizes to MoS_3 and sulfur or SO_2. Oxide films begin to be formed at 350°C, and at a temperature above 480°C rapid oxidation of MoS_2 occurs. In a vacuum MoS_2 is stable up to a temperature of 1100°C. Molybdenum disulfide possesses high radiation resistance. The coefficient of friction during lubrication with MoS_2 decreases with an increase in the rate of slip and specific pressure. The presence of water decreases the lubricating properties of MoS_2.

Graphite has a hexagonal type lattice. The distance between the atoms of carbon in parallel layers is 3.44 Å, and between the atoms in the layer - 1.42 Å. Graphite is obtained by the thermal treatment of coal, coke, and carbon black. It is a very effective laminated solid lubricant. At a temperature of 450°C graphite oxidizes. Water and adsorbed vapors considerably improve its lubricating properties.

Basic properties of graphite

Density............................. 2.24–2.25 g/cm^3
Porosity............................ 20–32%
Melting point....................... 3800–3900°C
Coefficient of linear expansion
  over the temperature range
  0–1000°C.......................... $(3.5-8) \cdot 10^{-6}$/°C

Limit of strength for tension...... 50–95 kg/cm^2

Limit of strength from com-
  pression.......................... 160–300 kg/cm^2
Modulus of elasticity.............. $5.6 \cdot 10^4$ kg/cm^2

Boron nitride BN crystallizes in a hexagonal system. Its crystal lattice is analogous to the lattice of graphite, in which one atom is substituted by boron, and another by nitrogen. The atoms of boron and nitrogen are located in alternate horizontal layers. The distance between neighboring layers for boron nitride is 3.34 $\overset{o}{A}$, which is somewhat less than in graphite and therefore the bond between the layers for BN is more durable, than for graphite.

Boron nitride possesses low electrical conductivity and high thermal stability. At high temperatures it oxidizes and forms boron oxide B_2O_3, which is also a good lubricant. The coefficient of friction of it is higher than for graphite and molybdenum disulfide.

Tungsten disulfide WS_2 has a hexagonal lattice similar to MoS_2 in which the atoms of molybdenum are replaced by atoms of tungsten. In comparison with molybdenum disulfide it possesses greater heat resistance, retains its lubricating properties in air to 510°C, and in a vacuum or in a medium of inert gas - to 1250°C. Tungsten disulfide is chemically inert, is insoluble in almost all media, including water, oil, alkali and almost all acids. It is not toxic and does not cause corrosion of metals.

Molybdenum diselenide $MoSe_2$ has a hexagonal lattice with parameters $a = 3.28$ $\overset{o}{A}$, $\sigma = 12.84$ $\overset{o}{A}$. The crystal lattice of $MoSe_2$ is similar to the lattice of MoS_2, in which the atoms of sulfur are replaced by atoms of selenium. Molybdenum diselenide does not oxidize in air up to a temperature of 400°C.

Tungsten diselenide WSe_2 has a hexagonal lattice of the molybdenum disulfide type, a solid lubricant, which operates for a long time in a vacuum at a reduced temperature in a oxidizing medium. In a mixture with other solid lubricants it gives compositions which possess a high effectiveness.

Apart from the above examined laminated solid lubricants, niobium diselenide $NbSe_2$, cadminum iodide CdI_2, antimony trisulfide Sb_2S_3, etc., are used.

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3. Solid Lubricating Films and Coatings

A positive gradient of mechanical strength during external friction can be obtained if a thin layer of metal which possesses a lubricating effect is applied to one of the surfaces.

Metal films as solid lubricants are used in friction nodes that operate in a vacuum under high loads and small rates of relative movement. Soft metals are used as solid lubricants: lead, silver, bismuth, gold, cadmium, etc.

Polymer lubricants are such as polyfluoroethylene resin (Teflon), capron, plastics based on phenol, find increasingly wider application. The high physical-mechanical and antifriction properties of the indicated plastics give the possibility to use them under conditions of inadequate liquid lubrication or its complete absence at relatively high and low temperatures. Polytetrafluoroethylene (Teflon) has received the widest application as a solid lubricant.

Ftoroplast-4 (Teflon) is a derivative of ethylene CH_2-CH_2. With the replacement in the latter of the atoms of hydrogen by atoms of fluorine tetrafluoroethylene is obtained CF_2-CF_2, which easily polymerizes with the formation of the polytetrafluoroethylene, known by the name Teflon $(-CF_2-CF_2-)_n$.

Teflon is a porous, fibrous, fine white powder which does not moisten in water and will not swell in it. In chemical resistance it exceeds all known materials, including gold and platinum, does not dissolve in one known solvent. Teflon operates over a temperature range of -269-260°C. A film of it retains flexibility at a temperature below -100°C and it does not become brittle in a medium of liquid helium.

Basic physical-mechanical properties of Teflon

Specific weight.............................. 2.35 g/cm^3
Melting point of crystals.................. 327°C

Temperature of decomposition.................... 415°C
Thermal conductivity.....(5.9-6.0) 10^{-4} cal/cm·s·deg
Specific heat capacity.............. 0.25 cal/g·deg

During the dry friction of metals on Teflon the coefficient
of friction, as a rule, is very small and does not exceed ordinarily
the coefficients of friction with liquid lubrication.

A molecule of Teflon has the form of a spiral with 13 atoms
of carbon in every spire. With such a location of atoms, a molecule
of Teflon has a cylindrical cross section, thanks to which it can
easily slide on neighboring molecules because the van der Waals forces
between the CF_2 groups of neighboring molecules are very small.

Composition lubricants are mixtures of dry lubricating
powders with binding substances. They are the most promising because
they make possible very effective laminated solid lubricants which
fasten solidly to the friction surfaces with polymer binders. Thermo-
plastic (alkyds, vinyls) or thermosetting (epoxy, phenol, melamine)
sodium silicate resins are used as binders. Inorganic binders are also
used - phosphates, borates. Alcohol, water, acetone, toluene, etc.,
serve as solvents.

4. Evaluation of the Physicochemical Properties of Solid Lubricants

Solid lubricants are used in friction nodes that operate under
very complex conditions (high temperatures, vacuum, aggressive media,
etc.). In order to judge the quality of a solid lubricant and its
fitness for a given friction node an evaluation is conducted of the
physicochemical properties of the solid lubricants according to a
number of indicators.

The thermal stability is evaluated by the maximum temperature
at which a solid lubricant retains its properties. During the
friction of two linked surfaces heat is liberated and as a result
the solid lubricant can be heated to very high temperatures. Measuring

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the temperature of friction and determining the moment when the solid
lubricant loses its lubricating properties (friction sharply increases,
wear rises, etc.), it is possible to evaluate the thermal stability
of a solid lubricant.

Chemical stability is the capacity of a solid lubricant
not to change its chemical composition during prolonged operation in
a friction node. A solid lubricant with poor chemical stability can
decompose with the liberation of corrosion active substances.

The thermal conductivity is an important operational property
of a solid lubricant. A solid lubricant with a good thermal conduc-
tivity rapidly draws heat away from overheated sections, and in
this way equalizes the temperatures in a layer of lubricant. Heat
which is liberated during friction, is transferred to the solid
lubricant and should further be dispersed as fast as possible, other-
wise local heating-melting of the lubricant and seizing of the friction
surfaces can occur.

The mechanical properties which characterize the deformation
and strength of a solid lubricant are very important when selecting
a lubricant for a given friction node. The most important of them
are hardness, compressibility, and tensile strength.

The microstructure, or aggregating, of the separate crystallites
of solid lubricants shows a large influence on their antifriction
properties. Separate crystallites connecting with each other can form
either a very dense monolithic, or a porous structure, and the
operational properties of the lubricant depend on this.

The dispersiveness, or the size of the particles, as a rule,
determines the specific surface and activity of a solid lubricant.
Other conditions being equal the smaller the size of the particles,
the larger the specific surface and activity of the lubricant. It
is necessary to focus attention on the size of the particles of a
solid lubricant both in the process of this production and during
use. Very thinly dispersed solid lubricants don't always possess

good properties. There exists an optimum size of the particles of a solid lubricant for every concrete case of its use.

The purity of a solid lubricant should be the highest. Substances which soil a solid lubricant can cause an abrasive effect, corrode metals, lower its thermal and chemical stability. Soiling of the solid lubricant is possible as a result of incomplete cleaning during its production or the process of use.

5. The Use of Solid Lubricants

Solid lubricants can be used in the form of powders, applied to the friction zone, thin coatings on the friction surface, and as component parts of structural antifriction materials.

Thin films of a solid lubricant preliminarily applied to friction surfaces receive the greatest distribution. In this instance the technology of applying the solid lubricant has a very large effect on its antifriction properties. Let us examine some methods of applying solid lubricants to friction surfaces.

Flame spraying. The powder-like solid lubricant, brought by heating to softening, is applied under pressure to a preliminarily prepared and heated metal surface. Then a coating is fused with a burner flame which facilitates obtaining a more uniform thickness and the formation of a smooth surface. The thickness of the coatings obtained by this method is 0.1-3 mm and depends on the size of the particles of powder.

Vortical spraying. The method of the vortical spraying consists of sinking a part heated to a determined temperature into the powder of a solid lubricant which is whirling or suspended in a jet of air. Falling on the heated surface, the powder sticks to it and forms a continuous layer. After removing the part from the apparatus the coating is fused with additional heating. The thickness of the coating depends upon the time of a stay in the "boiling" layer, the

temperatures of heating of the part, the thermal conductivity of the material, and constitutes 0.2-0.5 mm.

Vibration spraying. A part which is preheated to the melting temperature of the solid lubricant is sunk into a vibrating vessel with the solid lubricant powder. Because of the mobility of the particles of powder the part barely meets with resistance upon sinking into the vessel. Subsequent fusion occurs either because of the absorption of heat, or because of additional heating. Thickness of the coatings comprises 0.1-0.8 mm.

Centrifugal method of spraying. A part is heated 25-30°C above the melting temperature of a solid lubricant, whereupon it is covered with solid lubricant powder and placed into a centifugal machine for 5-10 min.

The method of applying composition lubricants to metal surfaces depends upon the composition of the lubricant and has a large effect on the operational properties of the coatings. The process of applying composition solid lubricants consists basically of the following operations:

cleaning the friction surfaces (degreasing, removal of corrosion products);

special treatment of the surfaces (phosphate treatment, sulfidation, electro-etching, etc.);

applying solid lubricant (with a brush, by spraying, by dipping);

consolidation of the lubricating coating by heating it in a thermostat.

Rotoprint method of applying solid lubricants. The essence of the method consists of the continuous application of a coating with the lubricating element, pressed to the friction surfaces with

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a certain optimum pressure, which provides for the formation of a lubricating film with minimum wear of the lubricating element.

It is possible to use pressed sulfides, selenides, and tellurides of molybdenum, tungsten, niobium, and graphite, and also various self-lubricating materials as a lubricating element.

In slip bearings the rotoprint system is accomplished in the form of inserts which are coated on the friction surface but which do not receive a working load. Into toothed gearing to create lubricant films idle gears of self-lubricating materials are used, which when they wear out lubricate the whole reduction gear. In ball bearings this function is accomplished by separators of self-lubricating materials.

The rotoprint method was developed in the laboratory of the theory of friction of the Institute of the Science of Machines, Academy of Sciences, USSR under the guidance of Prof. I. V. Kratel'skiy.

The friction method of applying films is used today for applying molybdenum disulfide. The essence of the method is that the powder is rubbed into the metal surface with the aid of special laps. In this case molbydenum disulfide forms durable adhesive films on the metal surface as a result of the high physicochemical activity of the juvenile (clean) surfaces of the metal.

The author of this book has proposed, for example, a method of applying thin films of molybdenum disulfide to metal surfaces by treating these surfaces with a special lap, into the grooves of which is pressed a thoroughly mixed mass from the molybdenum disulfide MoS_2 and BF-2 glue. By this method it is possible to obtain films 2-7 μm thick.

6. Brands of Solid Lubricants

The VNIINP-230 lubricant is obtained by mixing molybdenum disulfide powder with EP-096 epoxy resin. The lubricant is applied to the preliminarily prepared surface by spraying, sinking the part, or smearing. Hardening is accomplished in a furnace at a temperature of 100-190°C. The lubricant can be used at low rates of relative movement, but under high specific loads and temperatures to 200°C.

The [GAZ] (ГАЗ)* lubricant is formed by mixing molybdenum or graphite disulfide powder with ED-5 epoxy resin. The method of application and the area of application are the same as for the VNIINP-230 lubricant.

The VNIINP-229 lubricant is obtained by mixing the powders of molybdenum disulfide and sodium silicate in water. After spraying drying at 80-150°C is accomplished on the surface. The lubricant can be used in slip and rolling bearings that operate in a vacuum up to 10^{-7} mm Hg. A lubricant can operate at temperature of from -70 to 350°C, and in a vacuum or a medium of neutral gas - to 500°C.

The VNIINP-213 lubricant - a mixture of molybdenum disulfide powder with K-55 organosilicon resin. The method of application and the area of use are the same as for VNIINP-229 lubricant.

Composition of lead oxide (95%) and silicon dioxide (5%) is obtained by mixing the powders in water. After spraying onto the metal surface in the form of a film 0.025-0.05 mm thick heating is accomplished to a temperature of 900°C with subsequent cooling. The lubricant can be used in bearings at very high temperatures (to 650°C).

Lead oxide. Lead is applied to metal surface by metallization spraying with subsequent oxidation. The lubricant can be used at high temperatures (to 540°C) and in a vacuum to 10^{-6} mm Hg.

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*[Translator's note: GAZ = ГАЗ - expansion unknown].

Gold is applied in a thin layer to the balls and tracks of rolling bearings and can accomplish the role of a solid lubricant when the bearings operate in a vacuum to 10^{-6} mm Hg.

Electrolytic coatings with brass, bismuth, antimony, cobalt, sulfur accomplish the role of solid lubricant during the friction of metal surfaces with a small rate of relative movement and high specific pressures; they effectively avert the seizing of metals. The conditions of electrolytic coating were developed by Prof. N. L. Goliy.

AMAN's - self-lubricating materials used for friction nodes that operate without a liquid lubricant at low standard and elevated temperatures (from -100 to +300°C). The AMAN's (AMAN-1, -2, -4, -7) are obtained by mixing special resins with fillers; they can be effectively used with the rotoprint method of applying a solid lubricant to a friction surface.

Ftoroplast-4 and ftoroplast-40 and their compositions with fillers (molybdenum disulfide, graphite, and others) are applied to friction surfaces by gas flame or vortical spraying. The solid lubricant is used for slip and rolling bearings that operate in chemically active media at cryogenic temperatures in a vacuum.

Polyamides and their compositions with fillers (molybdenum disulfide, graphite) are applied to the friction surface by gas flame or vortical spraying. The solid lubricant is used for slip bearings that operate in slightly corrosive media at temperatures up to 200°C.

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C H A P T E R   XVII

SPECIAL LIQUIDS

1. Liquids for Aircraft Hydraulic Systems

Modern aircraft have a number of hydraulic devices, in which the working bodies are the liquids which possess determined properties. The operating conditions of the liquids in the hydraulic systems of aircraft are very complex. They operate in constant contact with the various materials of which the hydraulic system is made, the pressure of the liquids can reach 300 kg/cm^2 and more, the temperature can fluctuate from -60 to 50-100°C and higher which is explained by the friction when the hydraulic system is operating and by heating of the whole aircraft in flight. Liquids of the hydraulic system are throttled with a large drop in pressure through very small gaps, and also undergo the effect of high specific pressures on the surfaces of friction pairs.

On the strength of work conditions for liquids for the hydraulics of aircraft very rigid requirements are presented.

They should possess a gently sloping viscosity-temper ture curve and a low freezing temperature. The viscosity is one of the most important characteristics of hydraulic liquids. An excessive decrease in the viscosity at positive temperatures leads to leaking of the liquid through various joints and seals of the hydraulic system which causes a loss of pressure and slows down the action of units. The low viscosity of a liquid does not allow it to prevent dry and

semidry friction of the parts of the hydraulic system. The high viscosity of a liquid leads to an increase in the resistance to motion of a liquid through the pipelines, especially at low temperatures.

According to modern technical requirements the viscosity of liquids being used in the hydraulic systems of aircraft should not be below 10 cSt at 60°C and not higher than 2500 cSt at -60°C. Satisfactory viscosity-temperature characteristics of mineral liquids for the hydraulic systems of aircraft are obtained presently by thickening a light distillate of the kerosene type with viscous additives and by using synthetic liquids, in particular organosilicon-based liquids.

The methods for determining the voscosity of liquids have been described in Chapter II.

The liquids should possess a maximum chemical and mechanical stability. Of a liquid for hydraulic systems it is required that under operating conditions it does not change its physicochemical properties, be chemically stable in a thin layer, not form a sticky hardening film on surfaces, and not change its fractional composition.

The intensity of oxidation of a liquid depends primarily upon the temperature: with an increase in temperature the process of oxidation is accelerated several times. In connection with this the maximum working temperature of mineral liquids is limited to 80°C.

The mechanized impurities and water found in a liquid facilitate oxidation. The process of oxidation of some metals and alloys, cadmium and zinc-plated surfaces is considerably accelerated. To decrease the rate of oxidation of the liquids the surfaces of the parts of the hydraulic system are subjected to special treatment (aluminum are anodized, steel are blued, nickel-plated, etc.). To retard the process of oxidation various antioxidant additives are also used.

Liquids subjected to large mechanical pressures, in one way or another lose their initial properties. The viscosity of the mineral liquids under the prolonged effect of high pressures, and especially throttling with a large drop in pressures, decreases considerably (up to 50% of the initial value). The lubricating capacity of the liquid can simultaneously worsen. This occurs as a result of the mechanical destruction of the molecules of the liquid: the heavy molecules of the liquid, especially of viscous additives, under prolonged mechanical pressure are broken down into finer parts.

Some synthetic liquids are distinguished by the large mechanical strength of the molecules. Liquids should not cause corrosion of the metals of the hydraulic system. High temperatures and pressures facilitate the acceleration of corrosion, the rate of which also depends upon the physicochemical properties of the liquid.

At the present time various anticorrosion additives are used along with the protective coatings of parts of the hydraulic systems.

The liquids should dissolve less gases in themselves. All liquids possess a determined capacity to dissolve gases, which in a dissolved state do not influence their mechanical properties. However if the pressure at any point of a hydraulic system decreases, the gases are liberated from the solution in the form of fine bubbles, which, remaining in a suspended state, substantially influence the mechanical properties of the liquids.

The relative amount of gas that can be dissolved in a liquid (up to saturation), is directly proportionally to the pressure on the contact area. The volume of gas can be calculated according to the formula

$$V_r = k V_m \frac{p_1}{p_2}.$$

where V_r – the volume of dissolved gas, related to atmospheric pressure and zero temperature, cm^3; k – the coefficient of solubility

of the gas in the liquid; V_x - the volume of liquid, cm^3, p_1 and p_2 - the initial and final pressure of the gas found in contact with the liquid, kg/cm^2.

The solubility of gases in a liquid depends upon its brand. With a decrease in the density and an increase in the temperature the solubility increases. For light mineral liquids the dependence of the coefficient of solubility of the gases on the temperature can be expressed empirically:

$$\kappa 10^2 = 7.9 + 0.019t.$$

where t - the temperature of the liquid, °C.

With a decrease in the pressure or temperature a determined quantity of the gases is liberated from the liquid forming a mechanical mixture with the liquid, which negatively influences the operation of the hydraulic system. Furthermore, under determined conditions the presence of gases in a liquid can lead to the formation of foam, the presence of which causes a decrease in the lubricationg properties of the liquid, accelerates its oxidation, and facilitates corrosion of the metal parts of the hydraulic system.

The liquid should possess minimum compressibility because with compression with an increase in pressure work is spent which, with a decrease in pressure is not recovered.

The amount of compressibility depends upon physicochemical properties of the liquid. Thus, light mineral oil, being used in the liquid shock absorbers of aircraft landing gear is compressed with an increase in pressure of from 0 to 3500 kg/cm^2 (at standard temperature) by 17% of its initial volume; kerosene under these conditions is compressed by 8.5%. The compressibility of silicone-based liquids is approximately 50% higher, than for mineral-based liquids of the same viscosity.

Figure 119 shows graphs of the relative change in the volume

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of some liquids depending on the pressure and the coefficient of compression of a standard liquid used in the hydraulic systems of aircraft depending on the pressure.
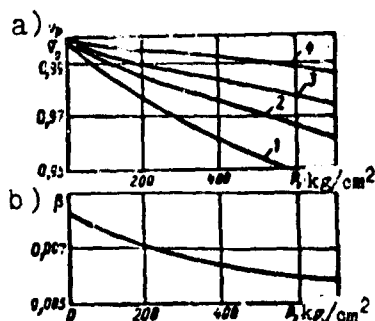
Fig. 119. Compressibility of liquids for the hydraulic systems of aircraft: 1 - silicone liquid; 2 - mineral oil; 3 - water; 4 - glycerine: a) dependence of the volume of the liquid on the pressure; b) dependence of the coefficient of compression on the pressure.

Liquids should possess a good heat capacity and thermal conductivity. The greater the values of the specific heat capacity and the coefficient of thermal conductivity a liquid has, the better it provides for the removal of heat from the hydraulic system. The specific heat capacity of a liquid is determined according to the equation

$$C_t = (0.345 + 0.000836 t)(2.1 - \gamma_{15}).$$

where C_t - the specific heat capacity of the liquid, kcal/kg·deg; t - the temperature of the liquid, °C; γ_{15} - the volumetric weight of the liquid at 15°C, kg/l, or

$$C_t = \frac{1}{\sqrt{\gamma_{15}}}(0.403 + 0.00081 t).$$

For widely distributed liquids the specific heat capacity in the temperature range of from 0 to 100°C are the following:

Mineral oil.. 0.45
Water-based liquids................................ 0.72
Glycerine.. 0.58
Kerosene... 0.50

Mineral liquids are poor heat conductors. For comparison the

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values of the coefficients of thermal conductivity in cal/cm·s·deg ×
× 10^{-4} of some liquids are presented below:

```
Water:
    at 10°C....................................... 14.7
    at 50°C....................................... 15.4
    at 80°C....................................... 16.0
Mineral oil at 15°C............................. 3.24
Castor oil at 20°C.............................. 4.32
Glycerine oil at 20°C.......................... 6.80
```

Brands of Liquids for Hydraulic Systems and Their Characteristics

The AMG-10 liquid (aviation oil, hydraulic) with a viscosity
not below 10 cSt at a temperature of 50°C is used basically in the
hydraulic systems of aircraft. The AMG-10 liquid is obtained by
thickening a low viscosity petroleum distillate with a high-molecular
polymer (vinypol VB-2). To provide for stability during a prolonged
period of service (two-three years) an antioxidant additive – naphtol
is added to the liquid.

The AMG-10 liquid causes swelling and the erosion of the skin
and nonoil resistant types of rubber. During the prolonged operation
of a liquid in a hydraulic system mechanical "grinding" of the viscous
additive occurs. Therefore it is necessary to pay attention to the
viscosity of the liquid during operation and with a decrease to 8 cSt
it should be replaced.

Technical norms for AMG-10 liquid

```
Appearance............................       transparent,
                                             red color
Viscosity kinematic, cSt at a tempera-
    ture of
    50°C..................................         10
   -50°C..................................       1250
Acid number, mg KOH per 1 g of liquid,
    not more than.........................  0.05
Test on a copper plate at 70 ± 20°C for
    24 h..................................       passes
```

The weight index of corrosion during a test of metal plates at 100°C for 168 h, not more than........................... ±0.1 mgf per 1 cm^2 of the metal surface

Stability at a temperature of 100°C for 168 h:
  viscosity kinematic after oxidation, cSt at a temperature of:
    50°C, not less than........   9.5
    -50°C, not more than.......   1500

Content of water-soluble acids and alkalis.....................   absent

Content of mechanical impurities.   absent

Water content.....................   absent

The flash temperature in an open type instrument................   92

Temperature of the beginning of boiling, °C, not below.........   200

The thickening temperature, °C, not higher than................   -70

The quality of the film of oil after holding it at 65^{+1}°C for 4 h........................   tape should not be solid and sticky over the entire surface of the plate

Density at 20°C, not more than...........................   0.850

For the shock absorber struts Li-2, Il-12, Il-14, An-2 aircraft and Mi-1 and Mi-4 helicopters AM-70/10 liquid based on glycerine is used which consists of 70% chemically pure glycerine, 20% ethanol and 10% boiled water by weight. Liquids based on glycerine have a number of substantial deficiencies. They are corrosion-active (especially at elevated temperatures), they give off silted deposits, glycerine in a thin layer saccharifies, the alcohol evaporates, and the liquid thickens. In connection with this AM-70/10 liquid has not been widely used.

Liquids for hydraulic systems based on mineral oils can be used for work under temperature conditions not higher than 120°C. With the use of inert gases in hydraulic systems which decreases the oxidation of a liquid, the maximum temperature can be raised to 180-200°C. However even at these temperatures mineral liquids operate

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unreliabily because the pressure of the saturated vapors rises and the danger of the pumps working in a cavitation mode appears. In connection with this for work under temperatre conditions above 150-170°C special synthetic-based liquids should be used. Specifically, organosilicon-based liquids find a use. Polysiloxane liquids have good viscosity-temperature characteristics, high mechanical strength, and resistance to oxidation. Furthermore, these liquids are fireproof.

Polysiloxane liquids dissolve all existing plasticizers of synthetic rubbers and therefore gaskets made of these materials become brittle, and as a result the units of the hydraulic system lose their airtightness. Polysiloxane liquids possess a high fluidity, in view of which the hermetic sealing of the units is complicated. Synthetic polysiloxane liquids possess poor lubricating properties. To increase the lubricating capacity of synthetic liquids additives and mineral oils are added to them.

2. Liquids for Combatting Aircraft Icing

During the operation of aircraft under conditions of low temperatures water from the air can condense and freeze on their surfaces (wings, fuselage, tail empennage, and others). Aircraft icing occurs both in flight, and on the ground.

Along with various heating and mechanical methods of combatting icing special de-icing liquids are widely used too. Ethanol and its mixtures with glycerine and water is used as the de-icing liquid which is used during flight to prevent the icing of some parts of an aircraft (glass of the cockpit canopy, propellers).

To prevent icing of an aircraft on the ground EAF (ether aldehyde fraction) and "Arctic" liquids are used today.

The liquid "Arctic" is transparent, colorless, odorless, possesses a low volatility, is flammable, and does not contain

mechanical impurities. The specific weight of the liquid at 20°C —
1.07 g/cm^3, the freezing temperature is -37°C. The liquid does not
cause the destruction of the varnish-and-paint coats of an aircraft
and the corrosion of metal parts, does not show a harmful effect
on sealing rubber and on the linen covering; it is used at temperatures
of the outside air down to -35°C.

The liquid is applied to the surface of an aircraft with the
aid of atomizing sprayers (expenditure 12-18 l/min at a pressure of
2-3 kg/cm^2). After the removal of the ice from the surface a
continuous thin film of the liquid, remains on it preventing the skin
from further icing.

Basic physicochemical properties of the EAF liquid

Appearance......................	transparent, yellowish color
Concentration, %, not below....	92
Temperature, °C:	
boiling......................	76-79
freezing.....................	-70
Viscosity, cSt, at a temperature of:	
0°C..........................	3.02
-10°C........................	3.86
-50°C........................	8.30

When using EAF liquid to combat the icing of aircraft on the
ground it is necessary to add to it 5" B-70 gasoline and 0.001 g of
the dye acid green per 1 l of liquid.

Before applying EAF liquid to the surface of an aircraft, the
ice already formed should r ~emoved and then the surface sprinkled
with a mixture of EAF liquid with water.

At a temperature to -8°C a mixture consisting of 50% (by
volume) EAF liquid and 50% water is applied; at temperatures from -8
to -25°C the mixture should consist of 60% EAF liquid and 40% water.
At lower temperatures pure EAF liquid is applied.

With proper handling, EAF liquid is practically harmless to the health of man. If this liquid gets inside it causes serious poisonings as a result of the presence of harmful impurities in it and especially methyl alcohol, 200-300 g of which cause death.

3. Washing Liquids

Today to clean soot and ground contaminants from the external and interior surfaces of aircraft, and oily and scaly contaminants from parts during the repair of aircraft and aircraft engines special washing liquids are used. In connection with the large variety of recommended liquids Table 45 gives the most effective ones.

Table 45. The composition of washing liquids and recommendations on their use.

Washing liquids	Use
35% ethylene glycol, 64.25% water, 0.5% oleinic acid, 0.25% mono-ethanolamine	In a preheated to 60-70°C state for cleaning ground contaminants and soot from the external surfaces of an aircraft at temperatures of the external air from 0 to -10°C
50% EAF, 49.25% water, 0.5% oleinic acid, 0.25% monoethanolane	For cleaning the external surfaces of an aircraft at temperatures of the external air from -10 to -25°C
75% EAF, 24.25% water, 0.5% oleinic acid, 0.25% monoethanolamine	For cleaning the external surfaces of an aircraft at temperatures of the external air from -25 to -45°C
97% water, 2% oleinic acid, 1% monoethanolamine	For washing an aircraft at positive temperatures of the surrounding air
97.5% water, 2.5% laundry soap	For washing aircraft at positive temperatures of the surrounding air
99% B-70 gasoline, 1% MK-8 oil	For cleaning the oil contaminants from the surfaces of an aircraft
95% water, 5% of the liquid "Progress"	For cleaning the interior surfaces of aircraft

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Table 45 (Cont'd.).

Washing liquids	Use
White-spirit (GOST 3134-52)	For cleaning aircraft power plants (propeller)
Phenol carboniferous creolin	For washing resinous deposits from air-oil radiators
60% technical tricresol, 40% ST-2 naphtha soap	For cleaning carbon deposits from engine parts
86.45% water, 10% naphtha soap, 3% phenol, 0.5% odorant, 0.05% dye	For servicing the toilets of aircraft
RDV solvent	For cleaning oil contaminints and varnish-and-paint coatings from parts during repair
AFT-1 wash liquid	The same
Aerol-1 - a one-percent solution of a paste-like concentrate, consisting of surface-active substances, fatty acids and sodium carbonate	For the removal of oil, oil contaminants, deposits of soot, dust, etc., from the surfaces of an aircraft

C H A P T E R   XVIII

TRANSPORTATION, STORAGE, AND SERVICING OF FUEL-LUBRICANTS AT AIRPORTS

1.   Transportation and Storage

The transportation of fuels and lubricants can be accomplished by all types of transport, but in this case the rules which prove for transportation safety and conservation of the properties of fuels and lubricants must be strictly observed.

Railroad transportation is accomplished in tank cars specially equipped for this. The tanks are distinguished by the type of product loaded - benzine, kerosene, oil, mazut, and bituminous. Draining the fuels and lubricants from the tanks is accomplished through cap hatches (upper drain) and through lower drainage devices (lower drain).

The transportation of oil products is possible smaller packages (steel and wooden barrels, cans), but a covered railroad car or containers should be used for this. Steel barrels and cans are intended for transporting and storing fuel, oils, and special liquids, and wooden - only for transporting and storing oils and lubricants.

The transportation of fuels and lubricants by water is accomplished either in special tankers, barages, etc., or on dry-cargo vessels in small packages.

Transporting fuels and lubricants by motor transport is accomplished in special tank cars of various carrying capacity and in small containers on board trucks and trailers.

The transportation of fuels and lubricants by air transport can be accomplished on cargo aircraft and helicopters in barrels and cans. Sometimes fuels are delivered in the tanks of aircraft. When transporting fuels and lubricants in an aircraft it is necessary to lay flooring of boards on the gang ways and floor of cabin, and the barrels or cans must be reliably fastened down. Fire extinguishers should be compulsory on aircraft.

Fuels and lubricants are stored in specially equipped storehouses which should be located outside the bands of air approaches in a specially removed are in accordance with the general plan of the airport. The location of storehouses should be connected with railroad, water and coastal facilities. The territory of the storehouse should be surrounded by a fence no less than 2.0 m in height and a fire-preventative water pipe should be laid into the storage area.

Storehouses for fuels and lubricants by designation are divided into storehouse of the first and second categories. The storehouses are connected with the airport by an automobile road, moreover, at storehouse of the first category usually not less than two accesses onto general use roads are made, and at storenouse of the second category one access is allowed. The road surface should provide for the passage of loaded fuel carriers. The network of roads and the access for fire-prevention goals in the area of the storage facilities should be a ring type.

2. Servicing of Aircraft

The capacity of the fuel tanks of modern transport aircraft with jet engines reaches 90,000 l and in proportion to the development of aviation is increasing all the time. Filling such volumes with filtered fuel in a limited time with observance of all the rules for

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servicing aircraft represents a complex technical problem.

At the present time this problem is solved by two principally different methods:

1. By using powerful mobile refueling units of a large capacity (40,000-45,000 l) and a large discharge capacity (up to 5000 l/min), With the aid of such refueling units it is possible to refuel an aircraft in 15-20 min.

2. With the aid of stationary servicing systems, when a supply of fuel is carried along pipelines from a central storage area to the parking spaces on the flight line. This method makes it possible to simultaneously refuel a large number of aircraft, without blocking in this case the takeoff field, platform, and the parking spaces of the flight lines with mobile refueling units.

Today in civil aviation airports the following mobile servicing methods are used: refueling units TZ-200, TZ-22, TZ-16, and oil servicing trucks MZ-150, MZ-51.

The refueling units accomplish the following operations:

fill their own tanks with fuel;

refuel aircraft with filtered fuel from their own and outside vessels;

they pump fuel over from one vessel into another, emptying their tanks;

blend fuel in the tank;

transport fuel.

The oil servicing truck accomplishes the following operations:

fills its own tank with oil;

pumps oil from one vessel into another, emptying its tank;

transports oil;

provides for the circulation of oil in a closed circuit.

Table 46 gives basic technical characteristics of fuel and oil servicing trucks.

Table 46. Basic technical characteristics of fuel and oil servicing trucks.

Characteristics	TZ-200	TZ-16	MZ-150	MZ-51	TZ-22
Landing gear..	MAZ-200	MAZ-204 semi-trailer and YaAZ-210D truck tractor	ZIL-150	GAZ-51	-
Operational capacity, l:					
tank..	7000	16,000	-	-	22,000
boiler (oil section)...............................	-	-	2100	920	-
Time to fill its own vessel with its pump,					
min..	20	20-35	-	-	18-20
Pump:					
type...	-	-	$PZ-30^3$	$PZ-30^3$	TsSP-57
quantity...	-	-	1	1	-
nominal number of shaft revolutions per					
minute...	-	-	1000	1000	-
Maximum pressure in the distribution system,					
kg/om^2..	3.5	3.5	4	4	-
Pumping capacity of the distribution system					
(oil at 85°C), l/min..............................	500	1000	210	175	1100
Fine cleaning filter:					
type...	TF-2M	TF-2M	-	-	TF-2M
quantity...	1	2	-	-	2
filtering surface, m^2...........................	1.2	1.6	-	-	-
Receiving hoses:					
quantity...	2	4	3	3	-
diameter, mm.......................................	65	76	65	65	-
length, m..	4.5	4.5	2.0	2.5	4.5
Distributing hoses:					
quantity...	2	2	1	?	2
diameter, mm.......................................	38	50	25	25	-
length, m..	20	20	9	10	20
Time for heating the oil from 10-20 to 100°C,					
min..	-	-	30-40	50-55	-
Mean rate of cooling of the oil, deg/h............	-	-	3-4	2-3	-

Fuels and lubricants are supplied to aircraft in accordance with the instructions in force at civil aviation airports.

The stationary servicing system is used basically at large airports for servicing heavy aircraft. A line diagram of one of the variants of stationary servicing is given in Fig. 120. As can be seen from the diagram, stationary servicing includes the reservoirs 1 for the storing of the fuel, pumping station 2, underground pipelines 3 and 4, and distributing point 5. In certain cases between the distributing point and the aircraft there exists one additional link - a mobile servicing unit 6.
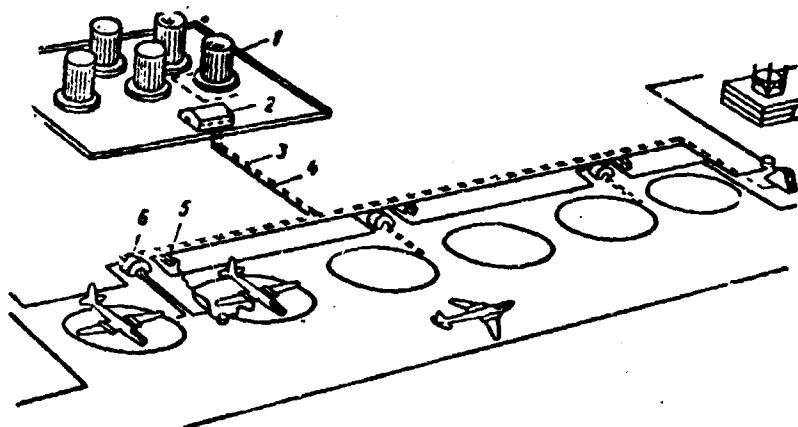
Fig. 120. Diagram of stationary servicing of fuels and lubricants.

Fuel from the service vessels is taken by the pumps and supplied through the pipeline to the aircraft servicing areas. Before entering the stationary servicing system the fuel is freed from water and the heaviest mechanical impurities, and then it passes through a filter-water trap and through fine cleaning filters. Further the fuel enters the main pipeline and network of pipelines, through which it is sent to the aircraft parking spaces.

Servicing the aircraft with fuel can be accomplished through the filling throats of the fuel tanks or from below under pressure. When servicing from below through special connecting pipes and tips the possibility of plugging the fuel tanks, and damaging the aircraft skin is excluded, the capacity for servicing increases, and the possibility of an accumulation of a large charge of static electricity decreases.

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Aviation propellants in the process of storage and transport
are soiled with mechanical impurities, which cannot be detected by
the naked eye. Mechanical impurities consist basically of particles
of iron oxide, sand, carbonaceous and fibrous substances, the sizes
of which vary over wide limits from 1-5 up to 80-200 µm. The greatest
number of the particles (50-55%) has sizes from 20 to 60 µm. Removal
of the mechanical impurities from the fuel is accomplished by repeated
filtration through fine filters. The fuel is also filtered by the
aircraft filters. The fine cleaning filters used today (paper, metal,
mesh) remove from the fuel all mechanical impurities more than 5 µm
in size.

Free water is removed from the fuels with the aid of the filter-
separators ST-500-2, ST-2000, and others.

3. Control of the Quality of Fuels and Lubricants

The development of aviation transport leads both to a further
increase in the quality of the fuels, lubricants, and special liquids
bring used, and to a growth in their quantity. Under these conditions
providing for the safe operation of aircraft in many respects depends
upon the reliable control of the quality of the fuels and lubricants,
which is accomplished systematically at various stages of the use of
the fuels, lubricants, and special liquids from the moment of their
acceptance at the airport into the aircraft.

As a rule, control of the quality of fuels and lubricants is
accomplished upon their acceptance at the airports, periodically
during storage, and directly before servicing into aircraft.

To maintain control of the quality of fuels and lubricants
special laboratories are organized at all large airports, and at those
places where there are none, the airport is attached to the nearest
large airport where such a laboratory exists. The assignment of the
laboratory control of the quality of fuels and lubricants is to
determine the basic physicochemical properties of the fuel,

lubricants, and special liquids and to determine their correspondence to the requirements of the standard or the technical conditions.

When receiving fuels and lubricants which come to the airport by any form of transportation, a sample is removed in which the physicochemical indicators presented in Table 47 (the column "before draining") are checked. Based on the results obtained checks and the data on the passport of the sender the type of fuel-lubricant is established along with the possibility of draining it into the airport vessels. Then the physicochemical indicators (column "after draining," see Table 47) are determined. If the fuel-lubricants are poured into partially filled vessels in the storage area, then after this a sample is removed from each vessel in which the indicators shown in the column "after draining" are checked.

Draining gasoline into reservoirs where the fuels T-1, TS-1, T-7, T-6, T-2 were stored and pumping the gasoline through the pipelines that were used for the indicated fuels can be accomplished only after thoroughly cleaning and washing the reservoirs and pipelines. Even an insignificant drop of T-1, TS-1, T-2, T-7 and T-6 fuels contaminates them. Such gasolines are categorically prohibited for direct use.

Before a laboratory check of the physicochemical indicators of the arrived fuel and lubricants, they cannot be used to service aircraft.

With prolonged storage of the fuels and lubricants at the airport a check of their physicochemical properties is accomplished 1 time in three months. If for any reasons it is necessary to drain fuel from an aircraft, it can be subsequently used only after determining the physicochemical properties shown in the column "during storage at the airport." In this case the drained fuel must be put into separate vessels according to brands.

For conducting laboratory analyses of the fuels and lubricants it is necessary to correctly accomplish selection of tests. The minimum test volume for conducting analyses is given in Table 48.

Table 47. List of the indicators of fuels and lubricants subject to a check at an airport.

Fuels, lubricants, propellants, and special liquids	Upon reception		During storage in an airport
	before draining	after draining	
Gasoline	Color and transparency Density at 20°C and at the temperature of measurement Content of mechanical impurities and water (qualitative determination)	Octane number Tetraethyl lead content Fractional composition Content of water-soluble acids and alkalis Content of actual resins	Density at 20°C and at the temperature of measurement Octane number Tetraethyl lead content Fractional composition Content of water-soluble acids and alkalis Content of actual resins Content of mechanical impurities and water (qualitative determination)
T-1, TS-1, T-2, T-6	Density at 20°C and at the temperature of mearurement Content of mechanical impurities and water (qualitative determination)	Fractional composition Viscosity kinematic at 20°C	Density at 20°C and at the temperature of measurement Fractional composition

Table 47 (Cont'd.).

Fuels, lubricants, propellants, and special liquids	Upon reception		During storage in an aircraft
	before draining	after draining	
Oil for piston aircraft engines	Density at 20°C and at the temperature of measurement	Content of water-soluble acids and alkalis	Content of actual resins
		Flash temperature in a closed type instrument	Acid number
	Content of mechanical impurities and water (qualitative determination)	Content of actual resins	Content of mechanical impurities and water (qualitative determination)
		Acid number	Viscosity at 20°C
		Viscosity kinematic at 50 and 100°C	Flash temperature in a closed type instrument
			Viscosity at 50 and 100°C
		Flash temperature in an open type instrument	Flash temperature in an open type instrument
		Content of water-soluble acids and alkalis	Acid number
			Content of water and mechanical impurities
			Coking capacity
			Content of water-soluble acids and alkalis

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Table 47 (Cont'd.).

Fuels, lubricants, propellants, and special liquids	Upon reception		During storage in an aircraft
	before draining	after draining	
Oil for jet aircraft engines	Density at 20°C and at the temperature of measurement Content of mechanical impurities and water (qualitative determination)	Viscosity kinematic at 20 and 80°C	Content of water-soluble acids and alkalis Acid number Content of mechanical impurities and water (qualitative determination) Flash temperature a closed type instrument
Consistent grease		Temperature of dripping Number of penetrations at 25°C Water content	Temperature of dripping Number of penetrations at 25°C Content of free organic acids
Liquids for hydraulic systems		Density at 20°C and at the temperature of measurement Fractional composition (for alcohol-glycerine mixtures)	Viscosity at 50°C Content of mechanical impurities Water content (for liquids based on petroleum) Acid number

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Table 47 (Cont'd.).

Fuels, lubricants, propellants, and special liquids	Upon reception		During storage in an aircraft
	before draining	after draining	
Ethyl fluid			Flash temperature in a closed type instrument Tetraethyl lead and scavenger content

Table 48. The volume of tests of fuels and lubricants necessary to conduct a laboratory analysis.

Fuels, lubricants, and special liquids	Volume of tests, %	
	control analysis	complete analysis
Aviation gasoline.................	0.7	2.0
Fuel T-1, TS-1, T-2, T-7, T-6......	0.6	1.5
Aviation oil......................	0.7	1.5
Consistent greases, kg............	0.5	1.0
Hydraulic system liquids..........	0.5	1.0
Ethyl cellosolve "A" (liquid "I").	-	0.5

Note: When determining the grade of gasoline 5 % are used for the test.

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Samplers are used for selecting samplers from reservoirs. There are samples, which make it possible to remove a sample immediately at any pouring height or after short intervals according to the pouring height in different quantities. It is also possible to use samplers, with the aid of which a sample is removed from determined given level (metal vessels or glass bottles in a metal frame). After selecting samples from different levels an average sample is prepared.

From a small package (barrels, cans) samples are removed with a tube 10-15 mm in diameter with a drawn end. Samples of greasy products are removed by a screw or piston probe or by a tube which has a lengthwise cutout over the entire length.

The stock for selecting the samples and the dishes should be clean. Before using them they are rinsed with the product from which the sample was removed if the product is liquid, or with gasoline if the product is greasy.

The method of selecting the samples is established as the following: from railroad biaxial tank cars one sample is removed from the middle of the tank, from tetra-axial - two samples: one at a distance of 200 mm from the bottom of the tank, and another at a distance of 200 mm from the upper level of a product. One average sample is prepared from equal parts by volume of the selected samples.

From horizontal stationary tank more than 2500 mm in diameter three samples are removed: the first 200 mm below the surface of the product, the second from the middle of the pouring height of the product, the third at a level of 250 mm from the bottom. An average sample is prepared from the selected samples by mixing one part of the first, six parts of the second; and one part of the third sample. Samples are removed from horizontal tanks up to 2500 mm in diameter in the same manner as shown for tetra-axial tanks.

For an average sample from a horizontal tank more than 2500 mm in diameter filled with the product to 1/2 the height three parts of

a sample selected from the middle of the height of the product, and one part of a sample selected at a level 200 mm from the lower edge of the receiving-distributing pipe.

Samples are removed from the small packages: from barrels - from 5% of the amount produced, but not less than from two barrels; from cans, bottles, and jars - from 2% of the amount produced, but not less than from two cans, bottles, and jars, Of the selected samples equal quantities by volume are taken and an average sample is prepared. Samples of the fuel are removed through the drainage valve of aircraft tanks.

Analyses of the samples of fuels and lubricants should be accomplished in strict accordance with existing standards. If while conducting an analysis an error or inaccuracy is introduced the analysis must be repeated. The results obtained are compared with the standard or the technical conditions for the given brand of fuel or lubricant, moreover if the results of the analysis coincide with the standard, the fuels and lubricants are considered standardized and can be introduced for use; otherwise it is categorically forbidden to use them directly. Based on the results of the analysis passport is issued on the established form.

Besides laboratory analyses, the airport control of the quality of fuels and lubricants is of great value. It is accomplished without an exception at all airports, and its mission is to provide for servicing of aircraft with fuels and lubricants without water and mechanical impurities.

Both fuels and lubricants is storehouse vessels and those issued for servicing and in the tanks of aircraft must be under airport control.

In the vessels at the storehouses the presence of water is determined daily with the aid of water-sensitive paper, paste, or visually in a sample taken from the vessel. The water in oils is

determined by the method of a crackling by preheating 1-2 ml of oil
in a test tube over a lighted match or alcohol. The mechanical im-
purities in oil are determined visually after a dilution in a glass
cylinder (250 ml capacity) of 40-50 ml of oil in a fourfold amount
of pure gasoline.

The secondary presence of water and mechanical impurities is
determined visually from the residue of fuel and oil servicing trucks
upon their arrival at the aerodrome.

And finally after servicing an aircraft with fuel it must
stand not less than 10 min, whereupon the sediment is poured out
and it is determined that there is no water and mechanical impurities
in it.

4. Safety Techniques when Working with Fuels and Lubricants

When handling fuels and lubricants it is necessary to always
consider their two important characteristics - flammability and
toxicity.

The flammability of propellants. Petroleum propellants used
in aviation are combustible easily ignited liquids, the vapors of which
form explosive mixtures with air. In connection with this under
operating conditions the propellant can itself be the source of a
fire with improper handling of it:

with the flash of fuel vapors from an open flame, an in-
candescent metal, or an electrical spark;

with the spontaneous combustion of a propellant in case it
falls on a heated surface, if its temperature will be higher than the
spontaneous combustion temperature of the propellant;

with an explosion of the propellant vapors in the gas space of

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tanks or other enclosed space with the appearance of a discharge of static electricity.

An evaluation of the fire danger of propellants is accomplished according to the following basic characteristics:

the temperature limits for the formation of the explosive mixtures of the fuel vapors with air;

the concentration limits of explosive mixtures;

the temperature of spontaneous combustion;

the flash temperature.

The flammability of the propellants is also determined by the rate of distribution of the flames. At the flash temperature higher above the open surface of the liquid fuel a combustible mixture forms. If this mixture is set afire, the flame will extend over the surface of the liquid fuel at a rate of 1.2-1.4 m/s. In an enclosed vessel the flame spreads at a rate of 0.3-0.6 m/s.

In the USSR and abroad the flammability of petroleum propellants is classified according to the flash temperature determined in a closed crucible. In accordance with this classification propellants of a wide fractional composition of the type T-2 and gasoline belong to the first class of flammability; T-1 and TS-1 fuels with a flash temperature of 28°C and above belong to the second class.

The concentration limits of explosive mixtures of various propellants are given in the Appendix.

The concentration of the fuel vapors in air can be calculated, if the temperature and the pressure of its saturated vapors at a given temperature are known using the formula

$$C = \frac{p_T \cdot 100}{p_{at}},$$

where C - the concentration of the fuel vapors in air, % by volume; p_T - the pressure of the saturated vapors, mm Hg; p_{at} - the pressure of a mixture of the fuel vapors with air (approximately equal to atmospheric), mm Hg.

The volumetric concentration of the fuel vapors in air can be recalculated by weight according to the formula

$$q = \frac{Cm}{2.24},$$

where m - the molecular weight of the fuel.

A very important characteristic of the flammability of a fuel is the temperature of spontaneous combustion. From the point of view of fire safety it is very important to know which temperature of an incandescent metal surface will cause ignition of the fuel that falls on such a surface (Table 49).

Table 49. Temperature of the spontaneous combustion of aviation fuels, °C.

Fuel	Flush temperature	Ignition temperature	Temperature of a heated plate that causes ignition	Fuel	Flash temperature	Ignition temperature	Temperature of a heated plate that causes ignition
T-1	30	220	325	T-2	-12	233	330
TS-1	28	218	325	T-70	-30	381	430

With an increase in pressure the temperature of spontaneous combustion of fuels drops.

Some combustible liquids can be intensively oxidized in air at relatively low temperature (16-20°C). Under determined conditions, when the amount of heat liberated in the process of oxidation will exceed the heat emission in the external medium, the spontaneous

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combustion of the liquid being oxidized can occur. Such liquids
are called self-igniting. Oils of vegetable origin and animal fats
are inclined to spontaneous combustion.

Electrification of propellants. During pumping with intensive
mixing and the transmission through a layer of fuel of a stream of
air, a charge of static electricity is formed in the propellant, the
discharge of which can lead to the ignition of the combustible mix-
ture, and this in turn leads to explosion and fire.

Studies conducted and detailed research on the facts of the
emergence of explosions and fires from static electricity made it
possible to establish a number of reasons for the formation of a
static electricity charge in propellants:

friction of the liquid propellant on the solid surface of the
pipeline, the reservoir walls, and the filter;

friction of the particles of propellant among themselves while
the propellant is moving through other liquids, for example water;

the passage of droplet of finely atomized propellant through
air or an air-vapor mixture;

precipitation of solid suspended particles from the propellant;

precipitation of liquid suspended particles, for example water
droplets or other chemical substances from the fuel, and also with
the passage of air bubbles, the vapors of light hydrocarbons, etc.,
through a layer of the liquid propellant;

passage of water droplets, snow flakes, etc., through an air-
vapor space.

It was experimentally established that the capacity of a
propellant to undergo electrification during pumping is found depend-
ing on its electrical conductivity: the less the electrical

conductivity of a propellant, the easier the charge of static electricity accumulates and the slower it is dispersed. Besides this, the rate of formation of static electricity is influenced by operational factors: the rate of pumping, presence of mechanical impurities, water, air in the fuel, the conditions of storage, the temperature, and others. The greater the pumping rate, the stronger the electrification of the propellant (Table 50). The longer the propellant is pumped the stronger it is electrified. A large effect on the electrification of propellants is shown by mechanical impurities and air bubbles: The more of them, the stronger the fuel is electrified. The water dissolved or dispersed in the propellant considerably increases the formation of static electricity. However water found on the bottom of a vessel in the form of a separate layer, either does not show an effect on the rate of formation of static electricity, or facilitates its decrease.

Table 50. Dependence of the size of the electrical charge of static electricity on the rate of circulation of gasoline.

Rate of circulation, m/s	Pipeline material	Electrical charge, V	Rate of circulation, m/s	Pipeline material	Electrical charge, V
1.0	Copper......	1000	1.3	Iron.......	2000
2.0	"	2000	2.5	"	3000

With the addition to the propellant of an insignificant amount of substances which step up the electrical conductivity (salts of alkali metals and others), the rate of formation of static electricity sharply drops, and in certain cases it is completely removed. At the same time the addition of carbonaceous substances to the propellant (asphalt, petroleum bitumen) in insignificant quantities (0.005-0.0005%) increases the capacity of the propellant to form static electricity during pumping.

In the process of storage the propellant oxidizes. When pumping the oxidized propellant, in which the content of potential resins has risen, its capacity to form static electricity increases very strongly:

Content of potential resins in a pro-
pellant, mg/100 ml................... 0.8   2.4   6.2
Number of discharges of static elec-
tricity in 10 min of pumping........ 21   5'¹   131

In order to prevent the emergence of fire from discharges,
caused by the electrification of the propellant, it is necessary to
observe the following measures:

carefully ground all the pumping equipment, pieplines, supply
and receiving tanks and reservoirs, automobile and railroad tank
cars;

not allow the pouring in the propellant in a falling stream
and the atomization or dispersion of it;

not allow the mixing of the propellant with the air, stream,
or gas and mechanical impurities, to avoid the suspension of
mechanical impurities from the bottom of the tank, not to allow the
entry of air into the propellants when pumping it into the reser-
voir;

in the pi·sence of floats in the reservoirs to ground them
to the body of the reservoir with the aid of chains or a flexible
conductor:

not to pump water-fuel mixtures and not to force out the pro-
pellant in a pipeline with water.

Toxicity of fuels and lubricants. Aviation propellants,
lubricating materials, and special liquids based on petroleum to one
degree or another are poisonous, if the necessary precautionary
measures in handling them are not observed.

Of all the possible type of poisoning by propellants the most
often encountered is poisoning by their vapors. Air is considered
safe for health only in the case when the quantity of propellant

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vapors in it does not exceed 0.5 mg/l. At higher concentrations poisoning can begin.

Two types of poisoning are distinguished: acute and chronic. With acute poisoning the development of sumptoms of poisoning occurs from several seconds (lightning form) to many hours after the beginning of the effect of toxic doses of the poisonous substances. Chronic poisoning develops as a result of the prolonged effect of low concentrations of the poisonous substances, which usually do not cause any indication of poisoning when breathed once or even over a period of several hours.

Acute poisoning sets in after 5-10 min when breathing air, in which the concentration of gasoline vapors constitutes 35-40 mg/l. When breathing air with smaller concentrations poisoning occurs after a certain period of time. Head pain appears along with an unpleasant sensation in the throat, a cough, irritation of the mucous membranes of the nose and the eye. If one remains longer in such an atmosphere, and also with an increase in the concentration of the gasoline vapors the indicators of poisoning are strengthened, instability of walking, dizziness, weakness, and excitation similar to alcoholic intoxication, dryness of the mouth, and nausea set in. If the stricken one is not taken to fresh air, loss of consciousness, strong cramps and weakening of respiration can begin.

Acute poisoning can also occur if gasoline enters the organism (sucking gasoline with the mouth through hoses, etc.).

Chronic poisoning by the gasoline vapors is observed with the systematic presence of them in concentrations exceeding allowable limits. The basic indicators of chronic poisoning are head pain, sluggishness, easily fatigued, losses of weight, irritability, sleepiness, or insomnia. As a result of the effect of the gasoline vapors chronic inflammation of the mucous membrances of the eye and diseases of the respiratory tract can appear.

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Gasoline can have a harmful local effect if it drops on the skin. It can penetrate the human body even through unbroken skin, however, since there are no provisions in the organism to accumulate it, it is rapidly eliminated through the lungs. This property of gasoline should always be remembered because together with gasoline the various substances dissolved in it can penetrate through the skin, for example tetraethyl lead, which possesses a tendency to accumulate in the organism and is able even in insignificant quantities to cause acute poisonings.

The vapors of kerosene more strongly annoy the mucous membranes and are more poisonous than gasoline vapors. However, since kerosene vaporizes considerably poorer than gasoline, cases of poisoning from kerosene vapors are noticed less.

The vapors of oils and petroleum based liquids are likewise poisonous, as are the vapors of gasoline or kerosene. However poisoning by the vapors of oils and liquids is an extremely rare phenomenon. Oil must represent a considerable danger for the organism. Breathing an oil mist with suspended particles from 1 to 100 μm in size causes poisoning. The danger of poisoning by the vapors or the mist of oils strongly increases, if sulfurous compounds are contained in the oil.

Ethyl fluid is a strong poison. With careless handling it represents a very large danger to health. The most poisonous component part of ethyl fluid is the tetraethyl lead, which easily penetrates an organism through the respiratory organs and is sucked through unbroken skin. The allowable concentration of tetraethyl lead in air is 0.000005 mgf/l.

A P P E N D I X

SOME INFORMATION DATA ON AVIATION PROPELLANTS, LUBRICATING MATERIALS, AND SPECIAL LIQUIDS

I. Aviation Propellants

1. Aniline Point, °C*

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T-1...................  57
TS-1..................  70
T-2 .................   59
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Note: Here and further on the information, marked *, is cited according to the data of K. K. Papi and N. A. Ragozin.

2. Viscosity

Dependence of the viscosity on temperature *

Temperature, °C	Kinematic viscosity, cSt			
	T-5	T-1	TS-1	T-2
—50	100,0	15,0	8,0	5,00
—40	50,0	9,0	5,0	4,50
—20	18,0	4,0	2,8	2,50
0	6,0	2,5	1,6	1,50
20	4,0	1,6	1,3	1,10
40	2,5	1,2	1,0	0,90
60	1,5	0,9	0,8	0,75

Viscosity at high temperatures (according to V. G. Malanichevaya).

Temperature, °C	Kinematic viscosity, cSt	
	T-1	TS-1
20	1,63	1,27
40	1,21	0,99
60	0,92	0,81
80	0,95	0,69
100	0,64	0,56
120	0,54	0,49
140	0,46	0,43
150	0,45	0,42

3. Evaporation of propellants

Evaporation from an open surface (according to N. A. Ragozin).

Propellant	Pressure of the saturated vapors at 38°C, mm Hg	Evaporation of propellant, %, from an open surface at	
		−10 °C	−15 °C
T-1	25	14,3	23,6
TC-1	35	19,3	30,0
T-2	80	26,4	35,0
T-2	100	31,4	41,0

Volatility of jet fuels (according to M. Ye. Tararychkin).

Temperature of the fuel, °C	Evaporation of fuel at an altitude of 18 km, %		
	TS-1	T-1	T-5
50	0,11	0,07	—
92	39,20	10,80	—
117	77,10	51,00	0,85
130	—	58,70	2,85

High-altitude characteristics of propellants (according to N. A. Ragozin).

Temperature °C	Altitude at which "boiling" begins, km				
	T-1	TS-1	T-2	B-70	B-95/130
10	23,0	22,0	18,7	14,0	12,7
20	20,5	19,3	16,2	11,8	11,1
30	19,5	17,8	13,9	9,6	7,5
40	16,9	15,4	11,8	6,9	4,7
50	15,0	13,1	9,5	5,1	2,3
60	12,8	11,2	7,6	2,7	—
70	10,4	8,0	—	—	—

Surface tension of jet fuels (according to
N. A. Ragozin).

Fuel	Density at 20°C	Surface tension, dyn/cm at 760 mm Hg and a temperature, °C of		
		10	20	40
T-1	0.81	26	25	24
TS-1	0.78	24	23	22
T-2	0.76	23	22	21
B-95/130	0.73	31	20	17

The surface tension of petroleum propellants can be calculated
with a slight approximation if its density is known*:

$$\Pi = 51.5d - 16.6.$$

where Π -- the surface tension at 20°C, dyn/cm; d - the density of
the fuel 20°C.

The heat of vaporization can be calculated with a certain
approximation according to the empirical formula of Gragoe

$$L = \frac{60 - 0.09t}{d},$$

where L - the heat of vaporization, kcal/kg; d - the density of the
fuel at 15°C; t - the average boiling temperature of the fuel, 0°C.

*The heat evaporation of the fuel (according
to Ye. R. Tereshchenko).*

Fuel	Heat of vaporization, kcal/kg		/Fuel	Heat of vaporization, kcal/kg
B-70	68		T-1	53
TS-1	56		T-5	48

*Coefficient of diffusion of the vapors of
T-5 propellant (according to
Yu. D. Vasilevekaya).*

Temperature, °C	Coefficient of diffusion at pressure 760 mm Hg	Temperature, °C	Coefficient of diffusion at pressure 760 mm Hg
0	0.0897	330	0.1356
250	0.1026	350	0.1440
270	0.1104	370	0.1532
290	0.1184	390	0.1635
310	0.1290	00	0.1640

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4. The Coefficients of Thermal Conductivity of Liquid Propellants Depending on the Temperature (According to A. V. Kozyukov)

Temperature, °C	Coefficient of thermal conductivity, kcal/m•h•deg		
	B-70	T-1	T-5
—50	0,1130	0,1090	0,1060
0	0,1035	0,1025	0,1020
50	0,0950	0,0958	0,0968
100	0,0884	0,0896	0,0922
150	0,0790	0,0830	0,0878
200	0,0688	0,0766	0,0824

The coefficient of thermal conductivity of oil-products in the temperature range of 0–200°C can be determined with an accuracy of up to ±10% according to the following empirical formula:

$$\lambda = \frac{101}{d}(1 - 0,00054t);$$

where λ – the coefficient of thermal conductivity, kcal/(m·h·deg); d – the density at 15°C; t – temperature, °C, at which the thermal conductivity is determined.

5. The Concentration of Sulfurous Compounds in Jet Fuels (According to Ya. B. Chertkov and V. N. Zrelov)

Fuel	Sulphurous compounds, discovered in fuels, % by weight			
	mercaptans	disulfides	sulfides	residual sulfur
TS-1	0,004	0,051	0,032	0,153
T-2	0,005	0,009	0,015	0,191

6. The Concentration Limits of the Explosiveness
of Mixtures of the Fuel Vapors with Air
(According to M. G. Godzhello)

Fuel	Density at $20^\circ C$, g/cm^3	Concentration limits of the explosiveness, % volumetric
T-1	0.813	1.43—7.10
TS-1	0.778	1.20—7.10
T-2	0.760	1.10—6.70

7. The Starting Properties of Fuels
(According to Ye. R. Tereshchenko)

Fuel	Pressure of vapors at $38^\circ C$, mm Hg	Temperature of boiling out of 10%, $^\circ C$	Minimum pressure of the fuel in front of the injector at which it is possible to start the engine, kg/cm^2
TS-1	40	153	8.0
T-1	30	168	9.0
T-5	15	210	13.0

8. Solubility of Water in Fuels, % by
Weight (According to N. A. Ragozin)

Fuel	$t = 38^\circ C$	$t = 0^\circ C$	Liberation of water from one ton of fuel, g
TS-1	0.011	0.0020	90
T-1	0.006	0.0018	53
Gasoline	0.013	0.0020	100

9. Compressibility of Fuels

It is possible to calculate approximately the coefficient of compressibility for fuels with a density of 0.80-0.95 according to the formula proposed by Prof. V. N. Vyrubov,

$$\beta = \frac{35 \cdot 10^{-6}}{d^2},$$

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where β - the coefficient of compressibility; d - the density of the fuel at 15°C.

10. Flash Temperature of Jet Fuels[*]

Fuel	Pressure of the vapors at 38°C, mm Hg	Flash temperature, °C
T-1	45	30
TS-1	50	28
T-2	75	— 4
T-2	100	—14
B-70	200	—28
B-95/130	320	—38

The flash temperature and the pressure of the saturated vapors are very sensitive indicators of the presence of gasoline in jet fuel which is illustrated by the following table:

Content of B-95/130 gasoline in TS-1 fuel, % volumetric	Pressure of the saturated vapors at 38°C, mm Hg	Flash temperature in a closed type instrument, °C
0	20	29
3	40	20
6	50	15
9	63	8
12	75	3
15	80	—2
18	90	—9

The pressure of the saturated vapors of a fuel can be for practical purposes calculated with sufficient accuracy according to the formula of M. Ye. Tararyshkin and O. M. Chechkina:

for T-1

$$\lg P = \frac{1954}{T} + 7.4112;$$

for TS-1

$$\lg P = \frac{1853}{T} + 7.089,$$

where P - the pressure of the saturated vapors, mm Hg; T - the absolute temperature of the fuel, $°K$.

*Pressure of the saturated vapors of fuels
(mm Hg), depending on the temperature*

Temperature, °C	T-5	T-1	TS-1	T-2
0	49	25	31	30
20	21	32	40	65
38	24	40	54	90
40	26	42	57	95
60	32	49	86	235
80	44	89	140	395
100	65	130	231	599
120	96	—	382	820
140	156	429	618	1280
160	245	675	969	1600
180	374	1046	1472	—
200	566	1527	—	—

11. The Thermal Stability Determined at a Temperature of 150°C for 4 Hours (According to N. F. Ronzhina)

Fuel	Fuel before the test		Presence of metal during the test	Fuel after the test		
	Actual resins, mg/100 ml	Acidity, mg KOH/100 ml		General sediment g	Actual resins, mg/100 ml	Acidity mg KOH/100 ml
T-1	3,4	0,65	VB-24 bronze	7,0	23,9	3,55
	3,4	0,65	Steel	6,2	15,2	2,58
	3,4	0,65	Absent	4,6	12,0	2,76
TS-1	4,4	0,82	VB-24 bronze	8,2	19,2	4,20
	4,4	0,82	Steel	7,0	16,8	2,46
	4,4	0,82	Absent	1,4	10,0	2,15
T-2	3,2	0,43	VB-24 bronze	0	4,9	0,22
	3,2	0,43	Steel	0	4,7	1,15
	4,4	0,02	Absent	0	3,5	0,10

Gumming of jet fuels under the effect of high temperatures during a 10-hour liquid-phase oxidation (according to M. P. Alekseyeva and R. S. Kasparova).

Temperature, °C	T-1		TS-1		
	Acidity, mg KOH/ 100 ml	Actual resins, mg/100 ml	Insoluble sediment, mg/100 ml	Acidity mg KOH/ 100 ml	Actual resins, mg/100 ml
60	0,35	4,0	—	0,25	10,5
80	0,35	4,0	—	0,25	11,5
100	0,40	6,0	—	0,35	10,5
110	1,27	16,5	0	0,90	12,5
115	2,60	17,0	4	1,53	12,0
120	3,92	20,5	5	1,53	15,5
125	4,72	26,0	7	2,52	15,0
130	6,17	34,5	8	3,16	19,0
135	6,73	—	10	—	22,5

12. Heat Capacity of Fuels (kcal/kg·deg) Depending on the Temperature (According to Ye. N. Pyatibratov)

Temperature, °C	B-70	T-1	T-5
20	0,492	0,478	0,466
40	0,514	0,499	0,486
60	0,536	0,522	0,529
80	0,562	0,544	0,529
100	0,587	0,568	0,551
120	0,613	0,592	0,574
140	0,641	0,616	0,596
160	0,668	0,640	0,619
180	0,697	0,666	0,643
200	0,727	0,690	0,666
210	0,742	0,703	0,678

13. The Stability of Burning of the Fuels in a Gas-Turbine Engine (According to Ye. R. Tereshchenko)

Fuel	Coefficient of the excess of air	
	that corresponds to disruption of the flame when the mixture is made lean	that corresponds to the appearance of a tongue at the outlet from the combustion when the mixture is enriched
B-70	16,8	3,44
T-2	14,4	3,63
TS-1	11,9	3,63
T-1	10,6	3,82
T-5	9,3	3,90

1. Viscosity

Viscosity of consistent greases (according to V. V. Sinitsyn).

Grease	Viscosity, poise, at the rate of deformation, s^{-1}			
	4	40	400	4000
Fatty grease, US-2..............	2200	302	55,0	14,5
Synthetic grease USs-2..........	1800	190	52,0	24,0
TsIATIM-201.....................	1860	275	33,5	6,6
UNZ.............................	2700	795	245,0	—

Interior diameter of the capillary viscosimeter for measuring the viscosity of various oils.

Oil	Internal diameter, mm, for measuring of viscosity at a temperature, $^{\circ}$C	
	50	100
Transformer........................	0,8	—
Turbine............................	1,0	0,6
Machine............................	1,0—1,2	0,8
Tractor............................	1,2—2,5	0,8
Aviation...........................	1,5—1,7	1,0

The viscosity of oils at low temperatures (according to G. I. Fuks, T. G. Mikhaylova, V. F. Yegorova).

Oil	Viscosity of oils in the RV-7 rotary viscosimeter, poise, at temperature, $^{\circ}$C			
	0	-10	-25	-40
Machine SU................	24,0	81,0	—	16 000
Aviation MS..............	80,0	510,5	17 000	464 000

Viscosity of oil diluted with gasoline (according to M. P. Volarovich).

Temperature, °C	Viscosity of MK oil cSt, with gasoline content, %		
	0	10	20
50	1,71	0,58	0,22
0	134	14,7	2,20
—10	386	40	4,8
—20	2 540	132	12,3
—30	15 000	466	32,0
—40	180 000	1 930	100,0
—50	4 300 000	9 600	395,0

Viscosity of MK-8 oil at low temperatures.

Temperature, °C	Kinematic viscosity, cSt	Temperature, °C	Kinematic viscosity, cSt
50	8,57	—20	482,00
0	88,80	—30	1496,00
—10	189,00	—40	6733,00

Starting viscosity of oils (according to published data the starting viscosity v = = 9000-10,000 cSt) depending on the dilution with gasoline.

Gasoline content in the oil, %	Temperature at which the viscosity of the oils is not higher than 9000-10,000 cSt, °C	
	MK-22	MS-14
0	2	—10
10	—19	—35
20	—40	—64

2. Vaporization of MK-8 Oil During Work in an Engine

Boiling out, %	Temperature of boiling out, °C		
	Fresh oil	Oil after 50 h of work	Oil after 100 n of work
Beginning of boiling	270	310	335
10	310	335	335
20	335	345	360
40	350	355	370
50	355	360	375
60	365	365	385
70	370	385	390
80	395	400	410

3. Concentration of Sulfur in Commercial Samples of Oil (According to S. T. Baybayeva and N. V. Salov'yeva)

Oil	Sulfur content, % by weight	
	Burning in a bomb	Burning in a lamp
MS-20	0.71	0.84
MK-8	0.10	0.14
Transformer	0.11	0.10
MK-22	0.14	0.15
MS-14	0.07	0.07

4. Lacquer Forming Capacity of Oils Depending on the Catalytic Effect of Metals (According to K. K. Papok and B. S. Zuseva). Oils were Heated for 30 min

Oil	Metal	Lacquer, %, at temperature, °C				
		250	260	270	280	290
MK-22	Steel 20	3	16	23	22	28
	Stainless steel	0	0	2	6	16
	Bronze	0	0	9	9	19
	Copper	0	2	7	8	14
	Duraluminium	0	0	0	4	19
	Aluminum	0	0	0	2	17
MS-20	Steel 20	9	19	24	25	19
	Stainless steel	0	7	17	20	--
	Bronze	1	2	4	9	19
	Copper	0	2	7	13	15
	Duraluminium	0	1	2	10	16
	Aluminum	0	8	8	16	—

*Lacquer forming capacity of MK-22 oil depend-
ing on the thickness of the oil layer (ac-
cording to K. K. Papok and by B. S. Zuseva).
Oil was heated for 10 min.*

Temperature, °C	Lacquer, %, with the thickness of the oil layer, μ m				
	10	60	100	150	200
200	0	0	0	0	0
220	15	0	0	0	0
240	26	6	0	0	0
260	18	24	1	1	0
280	10	26	16	7	3
300	9	22	25	18	12
320	0	17	23	24	20
350	0	11	18	20	21

5. The Washing Properties of MK and MS Oils Determined on a PZV Device, Balls*

MK......................... 4.5
MS (1st party)........... 4.0
MS (2nd party).......... 3.5

6. Pyrotechnic Characteristics of Oils (According to M. G. Godzhello)

Indicators	MK-22	MK-8	Transformer
Flash temperature in an open type instrument, °C........................	259	135	135
Temperature of spontaneous combustion °C.................................	390	310	300
Temperature limits of explosion-hazard mixtures, °C:			
lower...............................	238	120	122
upper...............................	254	160	163

7. The Lubricating Capacity of Oils During Testing on a Four-Balls Machine (According to L. V. Zhirnova)

Indicators	MK-8	MS-20
Viscosity of oils, cSt:		
at 50°C...	8,4	127
at 100°C..	2,97	20,3
Critical load, kg:		
at 20°C...	52—56	62—68
at 100°C..	48	56
Width of the wear of the balls, mm:		
at 20°C...	0,6—0,67	0,6—0,72
at 100°C..	0,50	0,96

8. Temperature of Preheating Necessary to Drain the Oil in Winter*

Oil	Necessary temperature of preheating, °C, during		
	storage before pumping	pouring into a tank	draining from a tank
MK-8	55	50	60
MS-20	55	50	60
MS-14	55	50	60
MS-24	55	50	60
Nigrol L	70	60	60

9. The Heat Capacity of Oils (According to L. V. Zhirnova)

Temperature limits for determining the heat capacity, °C	Heat capacity, kcal/(kg·deg)	
	MK-8	Transformer
50—19	0,467	0,463
100—19	0,493	0,495
150—19	0,510	0,536

10. Thermal Conductivity of Mineral Oils (According to A. K. Abas-Zade and R. A. Mustafayev)

Oil	$\lambda \cdot 10^{-9}$, kcal/(cm·s·deg) at temperature, °C				
	0	20	60	100	120
Transformer...............	312	306,0	295,0	282,0	276,0
Machine....................	338,5	332,5	323,0	312,0	306,0
Engine T (viscosity at 50°C equals 67.45 cSt)........	360,0	352,2	337,0	325,0	316,0

11. Elementary Composition of Oils (According to L. I. Saranchuk)

Oil	Viscosity at 100°C, cSt	Mean molecular weight	Elementary compostion, %	
			C	H
MS-20 (Emba)	20	550	86,30	13,70
MS-24 (Surakhan)	25	655	86,28	13,72

12. Hydraulic Liquids

Foaming (according to K. S. Chernova and V. A. Safanov).

Rate of the supply of air, cm³/min	Amount of foam formed, cm³		
	AM-70/10	AMG-10	MVP
50	5	50	100
100	12	65	—

Surface tension* at 20°C, dyn/cm

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AM-70/10...................... 41
AMG-10........................ 30
MVP........................... 31
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Pyrotechnic characteristics (according to M. G. Godshello).

Liquid	d_4^{20}	Temperature, °C		Temperature limits of the formation of explosion-hazard mixtures, °C	
		flash	spontaneous combustion	lower	upper
AMG-10	0,835	92	230	80	117
MVP	0,969	127	290	116	145

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